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CANBERRA, AUSTRALIA 1–6 December 2019

Supporting evidence-based decision making: the role of modelling and simulation

Abstracts

EDITOR: Elsawah, S

23rd International Congress on Modelling and Simulation

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DST Group led Defence Operations Research Symposium – DORS 2019

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DORS

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About the Modelling and Simulation Society of Australia and New Zealand

The Modelling and Simulation Society of Australia and New Zealand Inc. has been active since 1974, and has run the previous 22 MODSIM Congresses in Australasia.

The society represents modellers and managers with interests in using quantitative and qualitative methods to manage practical problems in industry, environment, science, societal and economics areas. It is affiliated with the International Association for Mathematics and Computers in Simulation. www.mssanz.org.au.

About the Australian Society for Operations Research

The Australian Society for Operations Research (ASOR) was founded in 1972 and has about 400 members nationwide. ASOR, like other national societies is affiliated to the International Federation of Operational Research Societies (IFORS).

ASOR serves the professional needs of OR analysts, managers, students and educators by publishing a National Bulletin and National and Chapter Newsletters. The society also serves as a focal point for operations researchers to communicate with each other and to reach out to other professional societies. www.asor.org.au.

About the DSTO led Defence Operations Research Symposium

The Defence Science and Technology Organisation (DSTO) Operations Research (OR) Hub provides a forum for the exchange of ideas and concepts in OR research efforts within Defence. The OR Hub runs the Defence Operations Research Symposium (DORS), an annual event, devoted to the practice of military operations research and analysis. The event covers a range of topics such as new OR techniques, novel approaches to the integration of techniques, and wargaming and simulation, presented in the form of OR case studies by a range of experts in the field.

About the 23rd International Congress on Modelling and Simulation (MODSIM2019)

MSSANZ, ASOR and DORS bring together a broad spectrum of scientists who apply various mathematical modelling, simulation, statistical, engineering, spatial and computer science methodologies and skills to solving practical problems coming from a wide range of endeavours. For them, the practical matter under investigation and the available data are the driving forces behind the methodology chosen for the task, or in developing techniques required to analyse new models.

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2	August 1976	Monash University, Melbourne, VIC
3	September 1978	Australian National University, Canberra, ACT
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5	May 1982	The University of New England, Armidale, NSW
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7	May 1987	Royal Melbourne Institute of Technology, Melbourne, VIC
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9	December 1991	Greenmount Resort Hotel, Gold Coast, QLD
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11	November 1995	The University of Newcastle, Newcastle, NSW
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13	December 1999	University of Waikato, New Zealand
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15	July 2003	Jupiters Hotel and Casino, Townsville, QLD
16	December 2005	Melbourne University, Melbourne, VIC
17	December 2007	University of Canterbury, Christchurch, New Zealand
18	July 2009	Cairns Convention Centre, Cairns, QLD
19	December 2011	Perth Convention and Exhibition Centre, Perth, WA
20	December 2013	Adelaide Convention Centre, Adelaide, SA
21	December 2015	Gold Coast Convention and Exhibition Centre, Broadbeach, QLD
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- **Associate Professor Barry Croke**, Australian National University, Australia
- **Professor Irene Hudson**, RMIT University Melbourne, Australia

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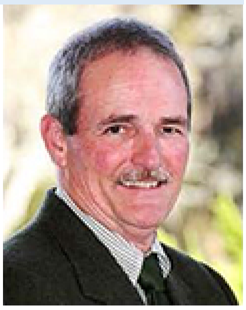
Emeritus Distinguished Professor Gerald G Brown



Naval Postgraduate School, California, USA

Guiding a path from problem to policy

Gerald G. Brown, Ph.D., is an Emeritus Distinguished Professor of Operations Research at the Naval Postgraduate School, where he has taught and conducted research in optimization and optimization-based decision support since 1973, earning awards for both outstanding teaching and research. His military research has been applied by every uniformed service, in areas ranging from strategic nuclear targeting to capital planning. He has been awarded the Barchi, Mennekin, Rist, and Thomas prizes for military operations research, is credited with guiding investments of more than a trillion dollars, and has earned the INFORMS President and Steinhardt Prizes for lifetime achievements. He has designed and implemented decision support software used by the majority of the Fortune 50, in areas ranging from vehicle routing to supply chain optimization. His research has earned patents and appears in scores of open-literature publications and classified reports, some of which are seminal references. Brown is an elected member of the National Academy of Engineering, a recipient of two US Navy Distinguished Civilian Service Medals, and an INFORMS Fellow. Brown is currently a Naval Postgraduate School volunteer who works with faculty in support of Navy education and research missions.

Professor Tatiana Filatova

University of Technology Sydney, Australia and University of Twente, The Netherlands

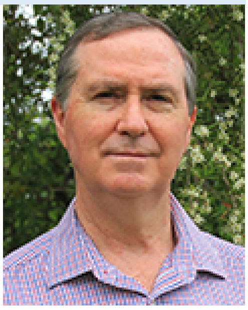
Adaptive human behavior and institutions in models of socio-environmental systems: in search for resilience in an urbanised world

Tatiana Filatova is Professor of Computational Economic Modeling at the University of Technology Sydney (UTS), Australia, and at the University of Twente, the Netherlands. Her research focuses on understanding where and how individual behavioral changes amplified by social interactions may cause structural changes in coupled socio-environmental systems. When studying these complex adaptive systems, she relies on agent-based computational models combined with behavioral data collection on individual decisions and social networks. Prof. Filatova applies these methods to explore economic impacts of disasters, urban resilience and regional dynamics. This research has been distinguished by a number of international awards and individual grants including the Early career NWO VENI grant and the ERC Starting grant. Professor Filatova is an elected member of the Young Academy (DJA) of the Royal Netherlands Academy of Arts and Sciences (KNAW), and serves as the scientific Program Leader of the **Dutch 4TU.Federation strategic research program on resilience** of social-technical-environmental systems (DeSIRE).

http://tatianafilatova.weebly.com/ and the UTS **PERSWADE** Research Center

Dr Paul Lawrence

Queensland Department of Environment and Science, Australia



The science-policy interface: A tale of interesting bedfellows

Paul Lawrence is the Acting Executive Director for Science Delivery and Knowledge in the Queensland Department of Environment and Science. He has over 35 years of experience in land and water processes, modelling, and decision support systems and has participated in national and technical advisory committees in natural resource management, reef water quality, land use planning and soil carbon. He is also the founding Director for the Queensland Water Modelling Network and Chairs the Steering Panel and Core Group. He has a strong interest in multidisciplinary science to inform policy and planning, and proactive in collaborative networks across government, university, industry and the private sectors. He holds a Bachelor and Masters Degrees from Griffith University, and a PhD from the University of Arizona in multiple criteria decision support systems. He has also completed an OECD Post-Doctoral Fellowship and an Executive Masters in Public Administration from Monash University.

Associate Professor Kate O'Brien

University of Queensland, Australia

Hazards of working across disciplines: how models (and modellers) can bridge the gaps

Associate Professor Kate O'Brien completed undergraduate degrees in Chemical Engineering and Mathematics at the University of Queensland (UQ) in 1994. She worked as a process engineer in New Zealand before completing her PhD in environmental engineering at the University of Western Australia, returning to UQ as an academic in 2002. Kate currently leads the chemical-environmental program at UQ. She has used mathematical modelling, data analysis and synthesis to provide insight into a wide range of sustainability issues, including greenhouse gas mitigation, the urban energy-water nexus, water quality and eutrophication, resilience of coastal ecosystems and work-family conflict. Kate takes a systems approach to sustainability, working in interdisciplinary teams with colleagues from engineering, ecology, business and social science.

Professor Karen Willcox

University of Texas, USA

Big decisions need more than just big data, they need big models too

Karen E. Willcox is Director of the Institute for Computational Engineering and Sciences (ICES) and a Professor of Aerospace Engineering and Engineering Mechanics at the University of Texas at Austin. She holds the W. A. 'Tex' Moncrief, Jr. Chair in Simulation-Based Engineering and Sciences and the Peter O'Donnell, Jr. Centennial Chair in Computing Systems. Before joining ICES in 2018, she spent 17 years as a professor at the Massachusetts Institute of Technology, where she served as the founding Co-Director of the MIT Center for Computational Engineering and the Associate Head of the MIT Department of Aeronautics and Astronautics. Prior to joining the MIT faculty, she worked at Boeing Phantom Works with the Blended-Wing-Body aircraft design group. Her research at MIT has produced scalable computational methods for design of next-generation engineered systems, with a particular focus on model reduction as a way to learn principled approximations from data and on multi-fidelity formulations to leverage multiple sources of uncertain information. She is a Fellow of SIAM and Associate Fellow of AIAA.

Professor Yongqiang Zhang

Chinese Academy of Sciences (Mid-career plenary speaker)

Large sample and high-resolution hydrological modelling studies to tackle a rapidly changing world

Dr Yongqiang Zhang has 20 years experience in hydrological modelling and remote sensing hydrology. He is currently a Distinguished Professor in the Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences. He worked in CSIRO as the Research Scientist, Senior Research Scientist and Principal Research Scientist in 2006-2018. He is currently the Associate Editor of Journal of Hydrology, the Associate Editor of Journal of Geophysical Research – Atmospheres, the Editorial Board Member of Remote Sensing of Environment. Dr Zhang published 150 peer-review journal papers, with majority published in leading hydrological and water resources journals, and > 60 papers published in the first author and/or corresponding author. He has Google Scholar citations of > 7100 and h-index 41 and ISI Web of Knowledge citations of >4000. He won 12 professional awards, including GN Alexander Medal and Alexandar von Humbdolt Fellowship.

Guiding a path from problem to policy

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Abstract: From the time an executive decides an important problem needs attention and arranges for our help, to when we succeed advising how to effectively address it, we analysts must fill a number of supportive roles. Lots of education is helpful, but it takes experience to learn what not to do. Typically, we are involved with three parties: the senior official who agrees the problem is worthy and authorizes analysis, the designated client intermediary for whom we work directly, and the "system operator" (the organization or protocol that must deal with the problem and any solution we propose). We must closely attend to the concerns of all these contacts, so we need to approach this with an analysis engagement plan. After admiring many successful engagements and those who headed them (and dissecting some signal failures) we find there is a certain sameness among the successes. Importantly, we find few differences between government and private sector, or military and civilian analysis projects (one refreshing exception in the private sector is to work for someone whose own money is on the table). This presentation suggests how to conduct an engagement to maximize your probability of success. This may suggest sensing initial tell-tales that advise turning down an engagement, to the benefit of all. This is not merely about formulating and solving some model (OK, this is the fun part of our jobs), but about constructively guiding the analysis through to influencing policy (and that is the most satisfying part). This may necessitate a lot of work not part of formal analysis: as one experienced colleague advises, "managing the engagement is 80% of the work, while the actual analysis is the other 50%".

This tempest will not give me leave to ponder on things would hurt me more.
But, I'll go in. Shakespeare, King Lear III (4:1826).

A longer exposition of advice and numerous concrete examples can be found in **INFORMS Analytics Body of Knowledge (ABOK)**, Wiley 2018, https://www.wiley.com/en-us/INFORMS+Analytics+Body+of+Knowledge-p-9781119483212, Chapters 6 (Modeling) and 7 (Machine Intelligence). Also see "How to Write about Operations Research," PHALANX, 37(3), 2004 https://faculty.nps.edu/gbrown/docs/Brown-%20howtowriteaboutor3.pdf. Over a trillion US dollars of decision support is reported here: https://faculty.nps.edu/gbrown/.

Keywords: *Decision support*

Adaptive human behavior and institutions in models of socio-environmental systems

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Abstract: Understanding and managing coupled social-environmental systems (SES) in the Anthropocene calls for an explicit representation of human agency in formal models. Evidence for regime shifts, adaptive behavior, changes in social norms and emergence of new socio-economic institutions – all reacting on and impacting environmental systems – grows. The simplified approach based on exogeneous scenarios of population, prices or GDP growth becomes increasingly insufficient to understand the dynamics of SES models, and consequently real SES where policy decisions, lives, livelihoods and ecosystems are at stake. Agent-based modeling (ABM) has developed as a method to simulate a number of heterogeneous adaptive agents – farmers, households, organizations or governments – that make decisions, learn and interact according to prescribed rules. In environmental modeling ABM is the preferred way to explicitly account for human behavior, and to quantify cumulative actions of various actors distributed over the spatial landscape. The number of ABMs explicitly simulating emergence and dynamics of formal and informal institutions, including markets and social norms, also increases. We witness more advanced, empirical ABMs being developed, with solid theoretical foundations for actors' behavior from social sciences, and integrating a variety of data sources to guide agents' behavior rules, interactions and learning in policy decision-support models.

In this talk I will discuss the state-of-the art in ABMs of SES and reflect on the open methodological challenges. In particular, I will elaborate on:

(i) the fact that there is a variety of social science theories that can provide microfoundations for agents' behavior when departing from rational optimizing assumptions and accommodating bounded rationality,

(ii) the possibilities to merge data from various sources, including GIS data, surveys, semi-structured interviews and even more qualitative data from stakeholders' workshops, and on how one can potentially use empirical data to address (i),

(iii) the implementation of learning in ABMs and use of machine learning methods to enable it,

(iv) scaling up of ABMs, since many of them are developed at urban and regional scales, while environmental models that that they need to talk to operate over larger geographical areas.

I will illustrate these issues going through a range of examples of ABMs of SES, including models of housing markets prone to urban floods, farmers facing droughts, and behavioral changes among households with respect to energy use.

Keywords: *Urbanization, resilience, floods, droughts, behavioral change, agent-based modeling*

The science-policy interface: A tale of interesting bedfellows

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Abstract: Simulation models have much to offer the decision making process. In the realm of natural resource and environmental management, models summarise a number of dynamic interactions between natural and physical processes, anthropogenic interventions of changed management, and in some cases, social disruptions. Models also provide tools for generating information that can be used to test 'what-if' scenarios or can be linked to multiple criteria decision support systems to identify preferred management systems in consideration of biophysical, economic and social factors.

In an ideal world, a policy practitioner or regulatory advisor armed with this information can explore opportunities and manage risks in developing a policy to achieve the desired outcome. However, when one thinks of policy designs, it is not uncommon to reflect on episodes of 'The Hollow Men' or 'Yes, Minister' to have a cynical perspective of the operations of government. And yet the role of public policy sets directions, implements regulations and meets national and international obligations on behalf of the community. In this context, what are the roles of models and modellers in the process of evidence-based policies, particularly when faced with 'wicked' environmental problems? Symbiotically, where are the intervention points in the policy making cycle that embrace scientific information and knowledge to craft good policy? And finally, at this interface between science and policy, how does each discipline contribute value to the other?

This paper will provide some insights to the opportunities and benefits for physically-based models to play in the policy space. It will draw on several case studies where the outputs and strategic application of models have demonstrated a structural underpinning to government policy. One recognised example is the operational use of catchment scale water quality models to inform the effectiveness of management actions for the Reef Report Card. Another is the combined use of the GRASP model and FORAGE to generate customised property scale reports to inform decision making for grazing land management. Notwithstanding the success of these, and other examples, any evaluation of model application exposes a soft underbelly of models, which includes the necessity to communicate the inherent assumptions in the model structure, the uncertainties in data over space, time and function, the dependencies on model calibration and validation, and the high level of information harmonisation that occurs in complex visualisations.

The paper will also present some principles that underpin effective processes to facilitate capacity on both the supply and demand side of the scientific advisory processes and to improve knowledge and practice at the interface of science and public policy. While the role of scientific evidence in supporting policy making is critical and timely, the pathway is neither straightforward, structured or guaranteed. These principles are focused primarily on communication and collaboration through arrangements of embedding and 'dialogue-hubs', and an ability to deliver 'fit-for-purpose' and relevant knowledge throughout the phases of policy development and implementation.

In reality, it is often less about the sophistication of the model or evidentiary information, but rather what you do with it.

Keywords: *Modelling tools, evidence-based policy, collaborative arrangements, Paddock to Reef, GRASP model*

Hazards of working across disciplines: how models (and modellers) can bridge the gaps

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Abstract: Climate change, water security, sustainable development - these and other wicked problems cannot be solved within any one discipline. Unintended consequences and perverse outcomes often arise from well-intentioned actions, because it's difficult to predict the future impacts of current decisions. Perfect forecasting wouldn't solve these problems either, because stakeholders disagree on what future they want, and who should pay for it.

Taming wicked problems therefore requires collaboration across traditional boundaries: not just between different branches of science, but right across the disciplinary divide to humanities, economics etc. Working across different fields of expertise is easier said than done, however. Building successful transdisciplinary collaboration takes time and effort, results are not guaranteed, and outcomes can be hard to publish. In an increasingly competitive job market, it can be risky to spread your finite resources too thin: moving between disciplines can make you a "jack of all trades, master of none". On the up side, crossing traditional divides brings inspiration and innovation: big advances often occur when ideas and techniques are taken from one field, and applied in a completely new context.

In this talk, I discuss how modellers can seize the benefits and avoid the perils of working across disciplines. Using examples spanning engineering, ecology and social science, I demonstrate how models can be used as a bridge across different areas of knowledge, enhancing collaboration by establishing a shared understanding of how a system works. Models can expose hidden assumptions, clarify trade-offs, identify missing information, highlight points of difference and tell stories.

Keywords: *Wicked problems, modelling, interdisciplinary, collaboration, transdisciplinary*

Big decisions need more than just big data, they need big models too

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Abstract: The field of data science has exploded in the last decade, not just in the realm of the internet and social media, but also for physical systems across science, engineering and medicine. This explosion of the field is fueled in large part by the explosion in volumes of data that are being produced. But it is also fueled by the availability of computing power and the tremendous progress in algorithms. We now have the ability to collect massive amounts of data, and we also have the ability to analyze it. The central question is: *How do we extract knowledge, insight and decisions from all of these data?*

Recent years have seen incredible success of machine learning methods in recommendation systems, social media, speech recognition, and more. But when it comes to high-consequence decisions in engineering, science and medicine, we need more than just the data. These decisions are almost always based on predictions that go beyond the available data. We often need to make predictions about a future state – about the future state of a patient's illness, about the states that an engineering system may find itself experiencing in operation, or about the future state of the Earth's climate in the decades to come. In these settings, there are multiple reasons that pure-data machine learning and statistical approaches will struggle to generalize with high confidence:

- The applications are characterized by complex multiscale multiphysics dynamics, so that small changes in parameters can lead to large changes in system behavior.
- The parameter space is very high dimensional. Many parameters of interest are fields (infinite dimensional). Without the constraints of physics, the solution space is so vast that driving decisions with data alone is doomed to failure.
- Data are sparse and typically rely on physical sensing infrastructure, making them expensive to acquire. Data may be large in volume, but they provide only limited peeks into the underlying high-dimensional parameter space.
- Uncertainty quantification of predictions must provide quantified confidence in the recommended decisions. This is especially challenging but especially important as we extrapolate beyond the data to issue predictions about future states.

This talk will introduce the notion of *Predictive Data Science*, which employs a synergistic combination of data and physics-based models. Learning from data through the lens of physics-based models is a way to bring structure to an otherwise intractable problem: it is a way to respect physical constraints, to embed domain knowledge, to bring interpretability to results, and to endow the resulting predictions with quantified uncertainties.

As one specific example, I will present “Lift & Learn”, a method that combines the perspectives of physics-based model reduction and machine learning, in order to derive low-dimensional approximate models that can be used for design and control. Model reduction brings in the physics of the problem, constraining the reduced model predictions to lie on a subspace defined by the governing equations. The machine learning perspective brings the flexibility of data-driven learning – in particular, flexibility in the choice of the physical variables that define the low-dimensional subspace. Combining the two perspectives, the proposed approach identifies a set of transformed physical variables that expose quadratic structure in the physical governing equations and then learns a quadratic ROM from transformed snapshot data. This learning does not require access to or interface with the high-fidelity model implementation, which is often cumbersome for complex engineering codes.

Keywords: *Predictive data science, scientific machine learning, model reduction, surrogate model*

Large sample and high-resolution hydrological modelling studies to tackle a rapidly changing world

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Abstract: We are living in a rapidly changing world, with geophysical datasets being created at fast increasing rates. How to better use these datasets for understanding hydrological processes in various climate, vegetation and anthropogenic-influenced regimes has become a challenge and an opportunity. This is particularly pressing for the hydrological community who have relied on lumped rainfall-runoff modelling for hydrological simulations/predictions over the last several decades.

This talk first discusses major challenges in catchment and large-scale hydrological modelling and predictions, including: (1) quantification of uncertainty in hydrological modelling related to model inputs, model structure and parameterization; (2） extrapolation of hydrological parameters for predictions in different periods of time, when land cover conditions and climate change rapidly; and (3) use of large sample and high resolution available data for insightful understanding and skilful predictions on water information. The talk then touches on opportunities for hydrological community for better and smartly use of large sample and high-resolution datasets for improving hydrological simulations and predictions. Incorporating the work conducted in the last decade, the author introduces and discusses following four topics:

1. Use of the Google Earth Engine platform. The author and his team used the Google Earth Engine platform developing PML-V2 model for estimating up-to-date 500 m and 8-day resolution actual evapotranspiration and gross primary production products across global land surface. This allows researchers to have comprehensive analysis on land cover change impacts on water and carbon fluxes from patch to global scales;
2. Developing state-of-the-art model-data fusion techniques for predicting runoff in ungauged catchments. The author explores the potential for using parameter values from hydrological models calibrated solely against readily available remotely-sensed ET data to estimate runoff time series. The advantage of this approach is that it does not require observed streamflow data for model calibration and is therefore particularly useful for runoff prediction in poorly gauged or ungauged regions. The modelling experiments are carried out using data from 222 catchments across Australia. The results from the runoff-free calibration are encouraging, particularly in simulating monthly runoff and mean annual runoff in the wetter catchments;
3. Modifying rainfall-runoff modelling structure for better incorporating remote sensing data. Since traditional rainfall-runoff models do not have structure to simulate impact of land use and land cover change (LUCC), they are not reliable to simulate hydrological processes with rapid LUCC. The author leads a team modifying traditional rainfall-runoff models by changing their submodule for describing soil moisture and actual evapotranspiration processes. The modified rainfall-runoff models improve hydrological simulations noticeably in the bushfire impacted catchments and other catchments experiencing rapid land cover changes; and
4. Using machine learning techniques together with large samples to improve predictions of various hydrological variables and hydrological signatures. Using a large sample dataset from 605 catchments across Australia, the author and his team explore the potential to use a machine learning approach (regression tree ensemble) for predicting 13 runoff signatures. The machine learning approach is then compared with three conventional approaches (multiple linear regression, multiple log-transformed linear regression and hydrological modelling). Results demonstrate that the machine learning approach performs best and offers significant potential, being able to predict most of the runoff signatures very well.

Keywords: *Hydrological modelling, remote sensing, large sample, high resolution, model-data fusion*

An improved stochastic modelling framework for biological networks

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Abstract: It has become very clear that stochasticity in biology is a rule rather than exception. Gillespie stochastic simulation algorithm (GSSA) (direct method) is the first algorithm proposed to model stochasticity in biochemical systems. However, the computational intractability of direct method has been identified as the main challenge for using it to model large biochemical systems. In this paper, a novel variant of the GSSA is proposed to address computational intractability of the direct method. The direct method is combined with a Mapping Reduction Method (MRM) to target a single run of the direct method to be accelerated by advancing the system through several reactions at each time step to replace the single reaction in GSSA. MRM is a framework for mimicking parallel processes occurring in large systems using a large number of threads that work together and seen as a single system. It is used for parallel problems to be processed across large datasets using a large number of nodes working together as a single system. Link between GSk3 and p53 in Alzheimer's disease (AD) is modelled using the proposed method and tested and validated by comparing it with the direct method.

The framework of GSSA/MRM includes four steps. These steps are initialization, election (mapping), selection (reduction) and updating. As shown in Figure 1. Initialization step is used to create a thread pool that includes T threads (reactions) and initialize the system by calculating the propensity function (a_j) for each reaction. Election step is mainly used to elect the number of threads equal to the number of reactions that have $a_j > 0$ to run GSSA. Each thread that runs GSSA is able to determine the next reaction j to occur and its time step τ. All reactions that are returned from the election step are filtered and only reactions that are able to fire are selected. GSSA/MRM is equal to GSSA if only one reaction is selected. If two reactions are selected and to reduce the number of time steps as GSSA does, the time step τ is the sum of the time steps from both threads. If more than two reactions are selected, the time step is calculated as the sum of the largest 3τ. Then, t is updated and the number of molecules is updated. The simulation is repeated until all possible reactions have been fired or the time of simulation is exceeded. This paper shows that GSSA/MRM is faster than GSSA due to the possibility of firing more than one reaction at each time step.

Keywords: *GSSA, MRM, Alzheimer's disease, p53, GSk3*

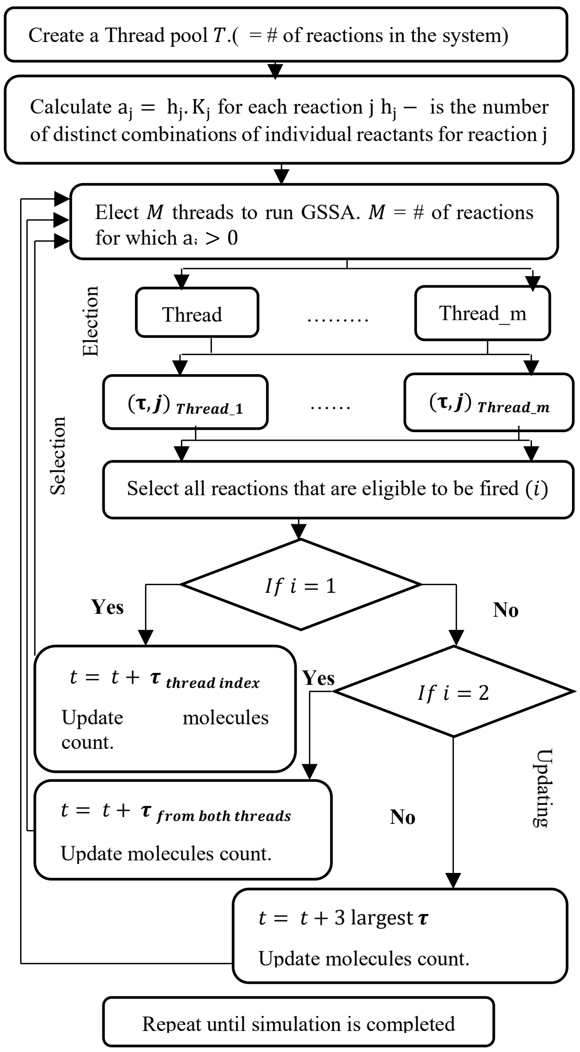

Figure 1. Schematic of GSSA/MRM

Modelling curvelet based signal processing problems via wavelet analysis

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Abstract: Until recently, the wavelet transform has been used for Mathematical analysis and signal processing problems. But it suffers from the disadvantage of poor directionality, which has undermined its usage in many applications. The curvelet transform is a new extension of the wavelet transform, which aims to deal with intersecting phenomena occurring along curved edges in 2-D signals/images. In this work, a strong relationship between the curvelet and wavelet transforms has been established. This version of a wavelet based curvelet has been exploited to develop a full-fledged analytical framework, presenting it as an extension of well established wavelets. Due to computational complexity, instead of applying a curvelet directly, the curvelet in terms of wavelets has been employed more conveniently in the proposed signal denoising model. Finally, the performance factor analysis is performed on multispectral sample radar image data to demonstrate the efficiency of the proposed model. Besides computational gain, the proposed model shows better performance than the other signal processing models. Proposed model is equally applicable to both pulse signals and digital images.

Keywords: *Wavelet transform, curvelet transform, signal processing, thresholding*

Some experiments in automated identification of Australian plants using convolutional neural networks

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Abstract: Accurate plant identification is a skill that generally requires considerable knowledge and advanced training. However, plant identification is useful to a broad range of people within society, from conservationists and farmers to citizen scientists. Access to accurate, widely available knowledge about the identity and distribution of living species is critical for biodiversity conservation and sustainable development.

Automated plant identification has undergone major advances since 2012 with the application of convolutional neural networks (CNNs) from the emerging field of deep learning. This branch of machine learning has shown remarkable accuracy in image classification and visual object recognition when applied to still images through competitions such as the ImageNet Large Scale Visual Recognition Challenge.

This research project used transfer learning to fine-tune pre-trained deep learning CNNs originally developed for the ImageNet challenge, such as Inception and ResNet, which are publicly available through Tensorflow Hub. The models were applied to the automated identification of images of plants extracted from the Australian National Botanic Gardens Australian Plant Image Index and validated using additional images from the Atlas of Living Australia (ALA) and other Internet sources.

A comparison of model performance was undertaken using three different datasets: whole plant images (9,612 images of 392 species with at least 20 images per species), images of flowers (3,384 images of 271 species with at least 10 images per species) and scanning electron microscopy images of liverwort spores from *Fossombronia spp.* (322 images of 12 species with at least 10 images per species).

To decrease the risk of overfitting and extend the training dataset, data augmentation techniques such as scaling and reflection were tested to identify a high performing method, which also improved overall model performance. The best performing model for the All-plants (80.6% accuracy) and Flower datasets (88.4% accuracy) was Inception_V3 pre-trained on the iNaturalist dataset of plants and animals. For the *Fossombronia spp.* dataset, the best performing model (81.2% accuracy) was ResNet_V2-50 pre-trained on ImageNet 2012, using the 50-layer implementation of ResNet_V2. The best performing flower identification model was also shown to have some proficiency in identifying the genus of an unknown species, where the genus but not species was represented in the dataset, with a Top-5 accuracy of 66%. The Flower dataset's best model performance was further tested using 1,000 images (20 images of 50 randomly selected species) downloaded from the Atlas of Living Australia and the Internet which produced a Top-1 accuracy of 85.9%.

Questions that remain to be addressed include further testing of data augmentation approaches and more comprehensive analysis to exclude overfitting. An interesting future extension of this study would be to train the best performing model on a larger dataset of Australian plant images, which could be used to aid scientists and the general public in identifying unknown species through image upload using an online website or phone app.

Keywords: *Convolutional neural networks, deep learning, plant identification, transfer learning*

Dynamics within and amongst Service-Provision Systems — A formal exploration using dynamical systems on graphs

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Abstract: It seems natural to think of products and services competing for consumer demand. This view suggests the use of models where those products and services are represented as simple entities in competition — e.g. Lotka-Volterra equations and agent-based approaches. However, knowing that products and services are provided by typically rather complex systems, the question arises whether such a view is justified. Can internal dynamics of systems safely be ignored when studying the dynamics *between* them? If the dynamics *within* systems are effectively decoupled from those *amongst* them, there would be theoretical justification for such a view.

To address this question, models of service-provision systems are introduced, in particular, of their supply chain network part. The networks are modelled by undirected graphs, with vertices representing organisations (firms, typically) and edges representing supply and service relationships. With each vertex i is associated a capacity $s_i(t)$, modelling the rate at which goods or services can be processed by that organisation. These capacities evolve according to ordinary differential equations (ODEs), coupling vertices that are adjacent in the network. Two sets of vertices, sources ($\hat{s}_i$) and sinks ($\check{s}_i$), are considered separately, representing inputs of resources into the system and the end-user demands, respectively.

The models are based on the following assumptions. Organisations that are *not* directly connected to either a source or sink, i.e. internal vertices, have 'synergistic' dynamics which minimises differences in capacity amongst adjacent organisations. In effect, each organisation is presented with a carrying capacity determined by its network neighbourhood. This leads to dynamical systems of the form

$$\frac{\mathrm{d}s_i}{\mathrm{d}t} = -v_i s_i + \sum_j w_{ij} a_{ij} s_j, \tag{1}$$

where a_{ij} is the adjacency matrix, w_{ij} are the edge weights and the v_i are intrinsic growth rates for each vertex. A non-linear (logistic) variant of these equations is also considered.

However, organisations directly connected to the same source or sink *compete*, which models the assumption that resources and end-user demands are scarce. Each such organisation is presented with a carrying capacity, reduced by the other organisations adjacent to the same source or sink. That is, to Equation (1) is added a term proportional to $-\sum s_j$, where the sum is over all $j \neq i$ adjacent to sources and sinks adjacent to i. This, in a way, provides the system with *boundary conditions*.

Though it may seem out of place to speak of boundary conditions in the context of ODEs, the equations thus obtained can be viewed as discrete analogues to continuous partial differential equations (PDEs). For example, taking v_i in Equation (1) equal to k_i, the degree of the vertex, and the weights w_{ij} to unity, one obtains $\mathrm{d}\vec{s}/\mathrm{d}t = -\Delta\vec{s}$, with Δ the *graph* Laplacian. Mentally omitting the minus the graph Laplacian carries where its continuous counterpart does not, this has the same form as the PDE for many diffusion phenomena. The PDE analogy is discussed in some depth and used to derive the preceding form from a continuity equation.

These models are explored analytically and solved exactly for a number of simple but illustrative cases. Several computer-simulated examples are also provided. It is found that for some models, away from the sources and sinks, the network dynamics equilibrate fast. Therefore, the view that the dynamics amongst service-provision systems is largely independent of the internal dynamics seems vindicated.

Keywords: *Supply chain networks, socio-economic networks, transitions, graph theory, dynamical systems*

Modelling cell aggregation using a modified swarm model

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Abstract: Cell aggregation and sorting are responsible for the formation, stability, and breakdown of tissue. A key mechanism for cell aggregations and sorting is that of cell-cell adhesion, a process by which cells bind or stick to each other through transmembrane proteins. This process is able to achieve cell sorting via the differential adhesion hypothesis (DAH) (Steinberg (1962b,a,c)). Armstrong et al. (2006) proposed a non-local advection model that was able to simulate the DAH. In their study, cells were modelled using a conservative system acting on cell density. The equations allowed for only two types of movement, random diffusive and directed adhesive movement with the adhesive movement taking into account cells within a finite sensing radius. Using the model with differing cell adhesion values they were able to simulate engulfment, partial engulfment, mixing, and sorting patterns between two cell types in both one and two dimensions.

The aggregation of cells can be considered as a type of swarming, in that it is the collective behaviour of a large number of self propelled entities (Loan and Evans (1999)). Examples of macroscopic biological swarms include locust swarms, ungulate herds, fish schools, bird flocks, etc. Non-local swarming models have been used to successfully model these phenomena (see Bernoff and Topaz (2013)). Based on the principle of conservation of mass, a fixed population density moves at a velocity that arises as a result of social interactions (Mogilner and Edelstein-Keshet (1999)), giving rise to an equation of the form

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (-\nabla (Q(x) * \rho)\rho) = 0,$$

with $Q(x)$ being a social potential function used to describe the social interactions between individuals.

In this paper we look at the Armstrong et al. (2006) model of cell-cell adhesion and recreate it by extending the swarm modelling techniques to equations of the form

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (-\nabla (Q(x) * f(\rho))\rho) = 0.$$

In doing so we find that by modelling in this way we are able to capture the same qualitative behaviour as the original model with a vastly reduced computational cost. We also derive a numerical scheme to simulate the model in one dimension in such a way that it can be easily adapted to other swarm problems. We find that the convergence rate of the numerical scheme is greater than 1.7 in all of the scenarios presented.

Keywords: *Cell modelling, numerical methods, swarm modelling, cell-cell adhesion*

Artificial Neural Networks & Random Forest Classification of druggable molecules and disease targets via scoring functions (SFs)

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Abstract: In recent years, machine learning has played an increasing role to help identify druggable molecules. In particular research has shown that random forests (RFs), recursive partitioning (RP), support vector machines (SVMs) and artificial neural networks (ANNs) have been commonly employed in this arena. Expanding disease modifying targets to pharmacological manipulation is vital to human health. Modelling disease targets allow for prediction and prioritisation based on their molecular characteristics and druggability. The aim of this current paper is 2 fold: (i) to propose a computational method to identify druggable disease targets using combinations molecular parameters (MPs) and (ii) to establish which of ANN or RF procedures and which scoring functions best partition molecular and disease target space. Classifications by Artificial Neural Networks (ANNs) and Random Forest (RF) based on 8 molecular parameters (MPs) were performed to classify disease targets with high or low violator scores (using cutpoints 3, 4 or 5), and the 4 traditional parameters of Lipinski's rule of five (Ro5), plus 4 extra parameters (polar surface area (PSA), number of rotatable bonds and rings, N and O atoms, and a choice between 2 alternatives for lipophilicity, the distribution coefficient (log D) and the partition coefficient (log P) (Hudson et al., (2017), Zafar et al., (2013, 2016)).

For the molecule parameter (MP) data RF performed better than ANNs and the log D model of either score 4 or score 5 was optimal compared to the log P model. ANNs however, were superior to the RF models for MP sets containing both log D and log P. For the RF score 4 log D model the most important variables were log D, molecular weight (MW) and number of rotatable bonds (ROT). The next best model via RF was score 5 log D, with its most important variables being PSA, log D and MW, according to mean decrease in gini scores.

Overall, for the target data the RF models performed better than ANNs, with inclusion of log D being important. For the RF target models the score 5 partition performed best, AUC (95% CI) of 0.88 (0.63, 1.0) for all 3 models; with the higher mean decrease gini values (MDGs) attributable to MPs (MW, NATOM, ROT, PSA Hacceptors, NRING). The MP variables then chosen with lower MDGs were (log D, NATOM, NRING, log P, Hdonors), indicating log D is superior to log P (VIs, 2.14 > 1.47). Also the RF score 4 log D, and log P models performed equally well, AUC (95% CI) of 0.85 (0.70, 1.00) - closely followed by the RF score 3 target models, score 3 log D and score 3(log D+log P), which both did well with AUC (95% CI) of 0.84 (0.73, 0.94).

The ANN target based score 4 log D model, achieved best classification, with AUC (95% CI) of 0.89 (0.77, 1.0). In contrast the score 4 log D+Log P model performed the worst, with AUC (95% CI) of 0.69 (0.51, 0.86). Similarly for the RF analysis, the score 4 log D+log P performed worse with AUC (95% CI) of 0.83 (0.68, 0.92), whilst separate score 4 log D or log P models classified equally well (0.85, (0.707, 1.0)). All 3 cutpoint 3 ANN target models, showed PSA to be highly important compared to the MW. In contrast MW is the most important variable for all RF target models and all cutpoints. Log D has greater variable importance (VI) compared to MW in the score 3 log D+log P ANN model (17.31 >12.60). Also in the score 3 log P ANN model, MW has least VI of 6.46 compared to log P's VI of 17.15. Log D is more important than log P in the score 3 log D+log P model.. For the optimal score 4 log D, model top VIs are attributable to (PSA, log D, NRING, Hacceptors, MW), showing strong influence of PSA and Log D compared to the traditional MW.

The RP and ANN rules to classify the high score violators from the low confirmed the value of log D in the scoring function, validating Zafar et al. (2016, 2013) and the original MC/DA cutpoints for each MP by Hudson et al. (2017). Score functions of violations and best cutpoints to identify druggable molecules and targets were confirmed and shown to be associated with specific diseases. Our simple scoring functions of counts of violations partitioned chemospace well, identifying both good/ poor druggable molecules and targets.

Keywords: *Disease targets, score function druggability rules, machine learning*

Detection of dairy cattle Mastitis: modelling of milking features using deep neural networks

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Abstract: Dairy cattle Mastitis is one of the most notable and costly diseases in dairy industry worldwide. The total Mastitis cost to dairy industry in New Zealand is up near $280 million a year; this cost includes drop in milk production, cattle treatment and other costs. This research includes the examination and analysis of data collected from a commercial robotic dairy farm, in order to design and build a computational model that can help efficient and accurate detection of Mastitis in dairy cattle herds.

Accurate Mastitis detection helps cut treatment costs, control the disease, retain milk production levels and maintain milk quality grade. In addition to cutting financial costs, efficient detection helps cows by protecting them and relieving pain caused by the disease. Computational models can help achieve these by helping farmers to adopt timely and suitable cattle treatment regime, and by preventing healthy cows from being infected.

For this study, robotic data have been collected for 12 months from a barn-based dairy farm at Makikihi in South Canterbury - New Zealand. At data collection time, that farm was the largest dairy farm in the world in terms of the number of milking-robots under one roof (24 milking robots in one barn). The collected dataset contains sensor data of more than 1,900 cows being milked more than 1.1 million times during the time of data collection.

Having about 29,000 milking instances fully labelled (healthy/sick), a deep neural network (DNN) was used to build, train and validate a classification model using variable combinations, including variables that have not been studied before. The model has shown the ability to perform detection tasks with a high level of accuracy; with Specificity (Sp) of 99%, and Sensitivity (Se) of 97%. With this high and stable Sp, and the relatively high Se, the proposed model avoids the problem of false positive alerts.

By using deep neural networks to build a Mastitis detection model, this study exploits the main characteristic that gives deep learning predominance compared with other techniques - representation learning, which means that the trained models can extract patterns that used to be ignored by other techniques, to present a robust definition of Mastitis, using real-world sensor data, generated by milking robots in a commercial dairy farm, including data for previously unexploited features. The results of this study allow viewing dairy cattle Mastitis detection from a different angle, which brings about a broader understanding of some of the signs and symptoms of Mastitis, leading to better control and management of the disease.

Keywords: *Mastitis, deep neural networks, dairy, keras*

Bushfire Emergency Response Uncertainty Quantification

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Abstract: Today, scenarios based on computer simulations are a fundamental tool for informing decision making at different levels of an organisation. When decisions concern the potential behaviour of complex systems, then uncertainty quantification (UQ) is paramount to provide appropriate levels of information for effective decision making. This is especially true for the Department of Defence which needs to make decisions on highly complex systems of systems, in uncertain future scenarios. However, it is useful to explore the tools and techniques required to analyse and communicate this uncertainty in an unclassified manner. Therefore, this project developed an unclassified, bushfire emergency response simulation to understand how to model, manage and communicate the impact of uncertainty in complex systems, as a surrogate for similar Defence problems. In this scenario, the fire is a threat and can exhibit behaviours characteristic of a complex system. The fire interacts with a network of response unit models, which in response to the complex behaviour of the fire, exhibit complex and uncertain behaviour, all while following mostly simple, deterministic logic. These models are comprised of the assets to be protected, command and control assets, fixed and mobile sensing assets, and assets within the response team with different capabilities to move and fight the fire (Fig. 1). The simulator is intended to capture key emergency response dynamic characteristics.

This is the first in a series of papers utilising bushfire emergency response simulation as a surrogate for Defence problems to explore the quantification of uncertainty in modelling, simulation and analysis of complex systems. This paper addresses the effects of input and output uncertainty, while future papers will address other sources of uncertainty, such as uncertainty in the operational environment, mission, agent behaviour, and importantly the communication of the impact of these various sources of uncertainty to decision makers.

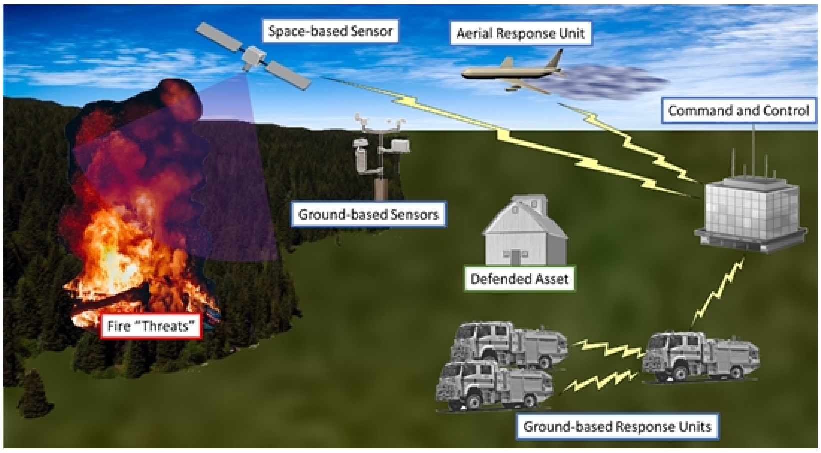

Figure 1. Simplified operational context diagram of bushfire emergency response.

Keywords: *Uncertainty quantification, bushfire emergency response, Monte Carlo simulation*

Bushfire Emergency Response Simulation

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Abstract: Improving the ability to model, manage and communicate the impact of uncertainty in complex interacting systems is becoming increasingly important. This is particularly important for defence as the nature of warfare is rapidly changing due to the incursion of novel defence technologies. The dominant attribute of modern warfare is its network-centric characteristic, which can be both an enabling and a limiting factor. Network-centric warfare refers to a potentially large number of entities or assets with varying capabilities for autonomous decision making whose coordinated fighting power is enabled through information exchange within a constrained system structure that can be described in terms of interacting networks. Such networks are known to be able to exhibit complex behaviours such as rapid phase transitions, oscillations, chaos, disturbance rejection, and adaptation. Understanding the potential for complex behaviours associated with particular military operations is essential to establish appropriate simulation and data collection processes that inform decisions about force design and asset acquisition. To explore these concepts in an unclassified manner, this project developed a bushfire emergency response simulator as a surrogate for similar Defence problems.

This paper describes our multi-agent simulation design which is intended to capture key dynamic characteristics of emergency response operations including individual fire response asset behaviours and team hierarchies in perception and decision making. This new bushfire emergency response simulator includes assets to be protected, command and control assets, fixed and mobile sensing assets, and assets within the response team with perception, decision, action and communication capabilities and with different capabilities to move and fight the fire. A new cellular automata type bushfire model with dynamical cell interactions considering fuel and wind is introduced, that enables simulation of a greater range of fire behaviours with higher fidelity, than simple cellular automata models.

This is the second in a series of papers describing bushfire emergency response simulation as a surrogate for Defence problems to explore the quantification of uncertainty in modelling, simulation and analysis of complex systems. This paper describes in further detail the bushfire emergency response simulator which was applied to uncertainty quantification in Bruggemann et al. (2019).

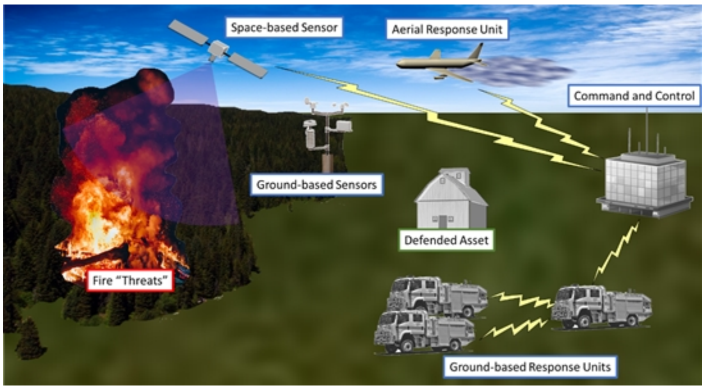

Figure 1. Simplified operational context diagram of bushfire emergency response.

Keywords: *Fire spread model, multi-agent simulation, cellular automata, Monte Carlo, bushfire emergency response*

Deconvolution for Oscillatory Shear Rheometry using the Landweber Iteration

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Abstract: In the deconvolution of convolution equations of the form

$$(p * h)(x) = \int_{-\infty}^{\infty} p(x-y)h(y)dy = g(x),$$

where the kernel p is specified explicitly, the goal is to recover from measurements g, estimates of the corresponding solution h. Such situations arise in a wide range of applications including, in rheology, the recovery of estimates of the storage and loss moduli characterization of a linear viscoelastic material from oscillatory shear measurements (Davies and Goulding 2012).

Various algorithms have been proposed for performing the deconvolution iteratively. The classical and historic example of the Neumann iteration has been examined in Anderssen et al. 2019, where conditions have been established that guaranteed its theoretical convergence. It is also noted that the corresponding numerical convergence is quite sensitive to the underlying frequencies in the discrete data g_n used to model g. Thus, the presence of noise, particularly at high frequencies, can give rise to poor convergence behavior. This leads to the idea that the numerical convergence might be improved by first smoothing the discrete data. One way of achieving this is to use the Landweber iteration (Landweber 1951), as it corresponds to generating the iterative solution of the least squares counterpart of $p * h = g$, namely $p * p * h = p * g$. It is shown that, though the Neumann iteration converges rapidly for smooth (exact) data, it performs quite poorly for noisy data, whereas the Landweber iteration, though slower, yields useful approximations in the presence of small noise perturbations in the data.

Consequently, for iterative schemes, such as that of Landweber, appropriate smoothing of the data must be used when working with experimental data.

Keywords: *Deconvolution, oscillatory shear, rheometry, Neumann iteration, Landweber iteration*

A functional strategy for nonlinear functionals

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Abstract: The linear functional strategy introduced by the first author in 1986 provided a shift in the way inverse problems were solved. It is based on the fact that for applications one is interested in specific properties of the solution of an inverse problem. These properties or quantities of interest are usually obtained by applying a functional to the solution of the inverse problem. The linear functional strategy avoided the need to solve the full inverse problem by solving the adjoint problem for the functional instead. The solution to this adjoint problem is a functional which, when applied to the data returns the quantity of interest. In some cases, the adjoint problem can be solved exactly. In any case, the adjoint problem does not need to deal explicitly with data errors.

In this paper we review the original approach. It is noted that any method which is able to produce an approximation to the solution of the adjoint problem which is continuous leads to a linear dependence of the error in the quantity of interest with respect to the data error.

Most of the paper considers the application of advances in computational and applied mathematics in the last 30 years to the functional strategy. We define a general (nonlinear) functional strategy and illustrate how this problem is solved. We define a generalised adjoint problem for nonlinear functionals and inverse problems. This adjoint problem is shown to be linear. Furthermore, we observe that nonlinear functionals which are Lipschitz continuous are stable with respect to data errors. The solution of the adjoint problem constrained to Lipschitz continuous functionals leads to Tikhonov regularisation.

We indicate how to implement the functional strategy for a simple example and provide links to modern functional analysis.

Keywords: *Functional strategy, inverse problems*

Stratified Space Learning: Reconstructing Embedded Graphs

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Abstract: Many data-rich industries are interested in the efficient discovery and modelling of structures under-lying large data sets, as it allows for the fast triage and dimension reduction of large volumes of data embedded in high dimensional spaces. The modelling of these underlying structures is also beneficial for the creation of simulated data that better represents real data. In particular, for systems testing in cases where the use of real data streams might prove impractical or otherwise undesirable. We seek to discover and model the structure by combining methods from topological data analysis with numerical modelling. As a first step in combining these two areas, we examine the recovery a linearly embedded graph $|G|$ given only a noisy point cloud sample X of $|G|$.

An *abstract graph* G consists of two sets: a set of vertices V and a set of edges E. An *embedded graph* $|G|$ in n dimensions is a geometric realisation of an abstract graph obtained by assigning to each vertex a unique coordinate vector in $\mathbb{R}^n$ and then each edge is the line segment between the coordinate vectors of the corresponding vertices. Given an embedded graph $|G| \subset \mathbb{R}^n$, a *point cloud* sample of $|G|$ consists of a finite collection of points in $\mathbb{R}^n$ sampled from $|G|$, potentially with noisy perturbations. We will suppose that this sample has bounded noise of ϵ and is sufficiently sampled so every point in $|G|$ is within ϵ of some sample. Such a sample is called an ϵ-sample.

We can view this as a semiparametric model. Once the abstract graph is fixed we have a parametric model where the parameters are the locations of the vertices. In order to guarantee correctness of our algorithm, we will need to make some reasonable geometric assumptions on the embedded graph.

To learn the embedded graph $|G|$, we first learn the structure of the abstract graph G. We do this by assigning a dimension of either 0 or 1 to each $x \in X$ (depending on local topological structure) and then cluster points into groups representing embedded vertices or edges. Using local topological structure, we then assign to each abstract edge cluster a pair of abstract vertex clusters, to obtain the incidence relations of the abstract graph. Finally, we use nonlinear least squares regression to model the embedded graph $|G|$.

The approach presented in this paper relies on topological concepts, such as stratification and local homology, which will be used in future research that will generalise this approach to embeddings on more general structures, in particular *stratified spaces*.

A stratified space $\mathbb{X}$ is a topological space with a partition into topological manifolds $\{X_i\}_{i\in I}$, called strata, such that for all i and j, $X_i \cap X_j = \emptyset$, and if $X_i \cap \overline{X_j} \neq \emptyset$, then $X_i \subseteq \overline{X_j}$.

If we are interested in a specific topological structure, we can require that the strata satisfy aditional criteria, so that this structure is constant across each strata. In the case presented in this paper, the vertices of a graph (abstract or embedded) are the 0-strata, and the (open) edges are 1-strata.

The authors are unaware of any algorithms which recover both the abstract graph, and model its embedding.

Keywords: *Stratified space learning, structure recovery, point clouds*

EXTENDED ABSTRACT ONLY

Near integrability in plasma dynamics

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Abstract: The construction of viable fusion reactors depends on our ability to control plasmas. These plasmas consist of charged particles interacting with electromagnetic fields. Much of the underlying dynamics in plasmas is still unclear. Key to our understanding of the dynamics would be an insight into the structure of magnetic fields as this structure dominates transport in magnetically confined plasmas. It is known that magnetic field lines are trajectories of Hamiltonian systems. In integrable Hamiltonian systems, there is a foliation by invariant surfaces containing the trajectories. Unfortunately, perturbations of integrable systems destroy integrability and irregular trajectories emerge. But even in this case, by the KAM (Kolmogorov-Arnold-Moser) theorem, periodic field lines and other less regular geometric structures do survive. Here we investigate (the existence of) coordinates which would generalize the classical action-angle variables of integrable Hamiltonian mechanics to nonintegrable cases such that these generalized action-angle coordinates permit us to understand non-chaotic regions of phase space of the perturbed Hamiltonian system. Such coordinates may also simplify the solution of a class of (nonlinear) non-isotropic diffusion equations.

Keywords: *Plasma confinement, toroidal magnetic fields, Hamiltonian systems*

The use of Bayesian inference to model complex systems

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Abstract: The use of Bayesian inference is flourishing among diverse fields, ranging from astronomy to climate science. The Bayesian approach to inference in fusion plasmas, developed by multiple authors [1,2,3,4], involves the specification of an initial prior probability distribution function, *P(I)*, for the vector of plasma parameters, *I*, which is then updated by taking into account information that the measurements provide through the likelihood probability distribution *P(D|I)*, where *D* is the measurement vector, and the notation *D|I* denotes a forward diagnostic model describing the response data *D* to plasma parameters *I.* The result is the posterior distribution *P(I|D)*, the conditional probability assigned after the relevant evidence *D* is taken into account, given by Bayes' formula *P(I|D) = P(D|I) P(I)/P(D).*

CI Hole and collaborators have developed a model validation framework based on Bayesian probabilistic methods to distinguish between competing equilibrium theories. Utilising this Bayesian framework, implemented in the code suite Minerva[5], we have: demonstrated current tomography using motional Stark effect observations, and data from magnetic pick up coils and flux loops[6,7]; developed a new diagnostic technique to identify and remove outlier observations associated with diagnostics falling out of calibration or suffering from an unidentified malfunction[8]; developed models for Thomson Scattering[9]; implemented nested-sampling[10], and optimised the posterior distribution [11]. We have also computed an estimate of the energetic particle pressure using a generalised force balance equation as a constraint [12]. The latter produces an energetic pressure profile whose core pressure is 30% of the thermal pressure - commensurate with other beam discharge plasmas with similar heating.

In this paper we review the use of Bayesian inference in plasma physics, its growing use in the inference of fast ions, and identify how these developments can be ported to other fields of research. An illustration is a project to develop Bayesian inference of global computer network dynamics using limited sensor data.

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Keywords: *Integrated modelling, Bayesian inference*

Model Order Reduction Techniques for Spectral Method Solutions of Hyperbolic Partial Differential Equation

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Abstract: Computational simulations are an important part of understanding and making predictions about the world around us. In many fields including astrophysics, fluid dynamics and operations research to name a few, simulating phenomena involves finding a solution to a system of partial differential equations (PDEs) given some input parameters μ which describe the system; this is the *forward problem*. For most PDEs, computational methods are required to find the solution.

Spectral methods are one family of computational techniques, which assume that the solution u to the PDE can be written as

$$u(x,t) = \sum_{k=0}^{\infty} \hat{u}_k(t)\phi_k(x), \tag{1}$$

where the $\phi_k(x)$ form a complete set of globally smooth basis functions. In a numerical implementation, the expansion is truncated to N terms. Using this decomposition, the PDE is re-formulated as a system of ODE which describe the evolution of the coefficients $\hat{u}_k(t)$. Spectral methods can accommodate higher order basis functions and hence greater accuracy and stability for given degrees of freedom when compared with finite element or finite difference methods.

However for complicated systems, even spectral methods can be computationally costly. This poses a challenge in applications that require solving the PDE for muultiple parameter values, such as

- optimising parameter choices for some quantity of interest, for example, the hape of a boat hull such that drag is minimised;
- solving an *inverse problem* such as determining the masses and spins of a binary black hole source given a gravitational waveform;
- uncertainty quantification, which often requires some sampling of the input parameter space.

For problems with high dimensional parameter spaces, repeatedly calculating the solution for sample parameter choices can become computationally infeasible. *Model order reduction* is a term given to a range of approaches that aim to replace the expensive, high-fidelity problem with an alternative problem with much lower computational complexity, while retaining accuracy.

This work examines accuracy, stability and computational efficiency for model order reduction techniques for hyperbolic PDEs. Using a spectral tau method for the high fidelity solution, we explore how the form of the parameter dependence in the PDE affects $\hat{u}_k(t)$. We then apply a range of model order reduction techniques to these, including PCA, the greedy algorithm, empirical interpolation and manifold learning.

Keywords: *Model order reduction, spectral methods, hyperbolic partial differential equation*

Developing a machine learning-based model to forecast growing season rainfall for Australian wheat belt

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Abstract: Long-term rainfall forecast for cropping areas can provide invaluable information for stakeholders to develop optimum farming strategies. Commonly used methods for rainfall forecast are either based on dynamical models or statistical models. Dynamical models mainly refer to general circulation models (GCMs), which are physically based models accounting for our understanding of the climate system. Rainfall forecasts from dynamical models can range from several weeks to a year. However, dynamical models are usually subjected to model bias and coarse spatial resolution (100-300 km). Moreover, the prediction skill of GCMs are highly dependent on climate forcings and initial conditions. Statistical models are achieved by modelling the relationships between rainfall and a set of potential predictors, such as lagged large-scale climate indices during past periods. Operational statistical models are usually based on limited number of predictors and linear regression algorithms. Thus, these models may fail to consider the effects of uninvolved indices and the nonlinear relationships between rainfall and predictors. Newly emerged machine learning algorithms, which are capable of exploring both linear and nonlinear relationships among a large number of variables, may help fill this gap.

Australia is a major food exporter in the world and most cereal products are produced along the Australian wheat belt. However, the Australian climate is highly affected by the variations of sea level pressure and sea surface temperature in the surrounding oceans, especially the Pacific Ocean and the Indian Ocean. In addition, the Southern Annular Mode, which describes atmospheric variability around Antarctica, also affect rainfall conditions in middle to higher latitudes of the southern hemisphere. In consequence, the Australian climate shows great inter-annual variability. A decline in rainfall amount across the Australian wheat belt may lead to a reduction in grain yield, which may then affect global food supply. However, few studies have been conducted to provide growing season rainfall forecasts for the Australian wheat belt. In this study, we firstly built a revised random forest model (a machine learning algorithm) to forecast growing season (Apr.-Nov.) rainfall anomaly based on a number of lagged large-scale climate indices, including Multivariate ENSO Index (MEI), Tripole Index for the Interdecadal Pacific Oscillation (TPI), Nino 3.4, Indian Ocean Dipole (IOD), and Southern Annular Mode (SAM). The result showed that the random forest model could potentially capture growing season rainfall anomaly, with r (Pearson correlation coefficient) ranging from 0.2 to 0.7 and d (Index of Agreement) ranging from 0.4 to 0.8. We also noticed that the random forecast model performed better in the east than in the west. This might be due to that western areas were relatively far from the Pacific Ocean, and were less affected by the conditions of the Pacific Ocean. In addition, some potential large-scale climate activities in the Indian Ocean and the Antarctica might not be captured by the IOD and SAM indices. Nevertheless, our study offered new insights into long-term rainfall forecast and can be easily extended to other areas of interest.

Keywords: *Australian wheat belt, growing season rainfall forecast, large-scale climate indices, random forecast*

Evaporation rates for a coral island by field observation and simulation

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Abstract: Evaporation in coral islands influences their limited freshwater recharge and plays an important role in coral reefs ecology protection under the background of climate changes. From June 20th to August 16th, 2018, a field experiment was carried out in Zhaoshu Island, Xisha Islands, China, using a self-made micro-lysimeter and pan evaporation dish. To understand the whole process of evaporations at the annual scale, we used the Penman-Monteith model and crop coefficient (Kc) method to estimate potential evaporation (ETo) and actual evaporation (ETc) using meteorological data and leaf area index (LAI). The results show (1) ETo reached its peak value earlier than precipitation, causing island vegetations to suffer the highest water stress at the end of the dry season. (2) in the wet season, ETc rose as the precipitation increased, however, the ETo presented a tendency of slowly declining. These phenomena indicate that the vegetation could suffer from strong drought at the end of the dry season because of the maximum ETo and extended low rate of precipitation. Therefore, more attention should be paid to this period.

Keywords: *Coral reef, micro-lysimeter, Penman-Monteith*

Bridging between mathematical and physically based models

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Abstract: In this presentation, the mathematical models will largely, but not exclusively, be represented by statistical and artificial intelligence techniques, whereas the physical model will be represented by process-based models. Examples of the different approaches are predictions derived from multiple linear regression or support vector machine regression, and the physical models by methods that involve existing knowledge of the underlying processes of the system that is being modelled. The mathematical models often are characterized by the lack of a physical interpretation of the reasons for the skill of the models. For example, high skill and the predictive variables are chosen by error minimization techniques, but no physical understanding of the predictor selection is explicitly provided. Hence domain knowledge is critical for understanding why the predictors are effective. On the other hand, physical models are built largely on domain knowledge, which then typically is converted to predictive formulae based on the understanding of the processes involved. In hydrology, and in many other geophysical applications the mathematical models include those derived from either archived observed data or by the mathematical representation of various conservation laws. That is, they can either be data-driven or by solving idealized governing equations. Alternatively, the physical models are derived from an understanding of the physical processes involved. Clearly, both approaches have had good success in modelling geophysical systems, suggesting the third path, which is a hybrid system based on combining mathematical and physically based models possibly could outperform either technique applied independently. Examples are presented, in both hydrological and meteorological contexts, and in a warming climate, of possible gains from using hybrid models.

Examples are from two very different locations. One is the impact of climate change on the heights of the Murrumbidgee River during 1961-2017. It is part of the Murray-Darling Basin (MDB). Its headwaters are in the mountains of southeast New South Wales (NSW), from which it flows westward until it joins the Murray River. Over the past 30 years, the Murrumbidgee River heights downstream at Hay, decreased noticeably. This steep decline is linked with decreased rainfall and increased evaporation, resulting from climate warming, in the Murrumbidgee source region wet season rainfall. A permutation test showed a statistically significant difference between the mean river heights at Hay between the periods 1961-1988 and 1999-2017 (p-value =0.032). A number of attributes were candidates were assessed as predictors, for the test data set (2000-2017). These attributes included ENSO-4, Global Temperature (GlobalT), Niño4 and Indian Ocean Dipole Index (DMI). Neural Nets (NN) uses the same attributes as Linear Regression (LR), whereas Support Vector Regression (SVR) uses GlobalT, Pacific Decadal Oscillation (PDO) and DMI. Random Forest (ERF) uses GlobalT and DMI. The correlations, after cross-validation, for predicting the river heights were, in descending order, 0.69 (SVR), 0.67 (NN), 0.53 (LR) and 0.47 (RF). Possible explanations for the relative performance of the four approaches will be discussed. The second example is the Ethiopian drought, which began in 2011 and continues to the present, as the Horn of Africa's recurring drought has been influence first by an El Nino event and, more recently, by a positive phase of the Indian Ocean Dipole. The scale of the Ethiopian drought is immense, affecting at least 10 million people. The entire Horn of Africa is facing a humanitarian crisis requiring emergency international support. For Northern and Central Ethiopia, the wet season is the months of June-September (JJAS). The best Machine Learning (ML) predictors for the upcoming JJAS rainfall are the August rainfall of the predicted season, which cannot be provided by the ML methods, for which the highest weights were assigned, in order, to the August precipitation anomaly, the Indian Ocean Dipole Index (DMI), and the ENSO region Nino34 SST anomaly. However, high resolution climate model projections, from CMIP-5, provide August rainfall predictions. Hence a hybrid model combination of ML and a CMIP-5 ensemble can provide JJAS seasonal rainfall predictions, using a combination of March-May data and the August CMIP-5 prediction. The predictive skill, was 80% correctly predicted above or below normal precipitation (Probability of Detection; POD) and 20% incorrectly predicted (False Alarm Rate; FAR). Further work on predicting both precipitation and mean temperatures is planned for both regions and also globally, for other drought affected areas.

Keywords: *Drought, river heights, machine learning, climate models, hybrid models*

Test the capability of artificial neural networks by using a univariate runoff forecasting for a data-scarce basin

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Abstract: Although artificial neural networks (ANNs) have been widely applied in hydrology for many years, the forecasting capability of ANNs in hydrology is still a not fully solved issue. It poses challenges to discuss the forecasting capability of ANN if using more input variables (for example precipitation, historical runoff, as been commonly utilized in many studies) than using only discharge data (univariate) as the input because usually more variables mean more uncertain factors involved. It is however meaningful to explore the forecasting capability of a discharge-based univariate ANN, as the discharge information carries almost all the information of runoff formation and runoff routing over a basin. Furthermore ANN is outstanding in its ability in deciphering the inherent nonlinearity than other univariate forecasting methods such as Autoregressive Moving Average model (ARIMA), which can basically only catch the linear relationships. Finally, this study tests the capability of artificial neural networks by using a univariate runoff forecasting specifically to the discharge data-scarce basins. By using the VIP (vegetation interface processes) distributed eco-hydrological physical processes-based model, which does not need data to calibrate the model, remote sensing and routine meteorological data, the historical discharge data are simulated. These data are then used to test the capability of the ANN, aiming to provide guidance if conjunctive use of a physical process-based model (VIP model) and a mathematical tool (ANN) can help runoff forecasting.

The historical daily data from January 1, 1956 to December 31, 2006 is simulated by the VIP model. In order to perform adequate demonstration about ANN, dataset is divided into calibration (from 1956 to 1994), test (from 1995 to 2000) and validation (from 2000 to 2006). Considering that different runoff formation mechanism during in different seasons (the nonlinear dynamics governing high, medium and low flow are varied widely; low flow is maintained by base flow; high flow is recharged by rapid surface runoff), constructing ANNs for low flow and high flow respectively is an effective approach to improve ANNs performance. This study does so by dividing the time series of runoff into low flow series and high flow series (briefly low and high respectively). Feed-Forward Neural Network (FFNN) is used as ANN model, which is compared with the one by conjunctively using wavelet transform (WANN) to deal with the possible concealed frequency in runoff time series to avoid data's non-stationarity. To avoid the possible randomness in giving a single initial values for each of the parameters to set the ANN structure (SFFNN and SWANN), the study also designed forecasting schemes by using the average of the multiple (here 100) initial values to each of the parameters of the ANN model (MFFNN and MWANN). Besides the essential single-step ahead forecasting, much further ahead forecasting (multi-step-ahead) are also given. Partial correlation and mutual information are used to select the key number of runoff points for the input of ANN.

Results show that generally, ANN can successfully issue a single-step ahead forecasting for daily-high, daily-low and monthly-low runoff forecasting. Although the forecasting remains poor, dividing the time series into wavelet series improves the monthly-high runoff forecasting. However, for already good performance (daily-high, daily-low and monthly-low), WANN made the forecasting performance even worse. If the behavioural threshold of Nash-Sutcliffe Efficiency (NSE) is set as 0.8, the ANN can issue a satisfactorily forecasting result 2 month ahead for monthly-low, 1 day ahead for daily-high, and 6 days ahead for daily-low. Giving multiple values to initial values does not improve the model performance significantly.

Keywords: *Runoff forecasting, artificial neural networks, feed-forward neural networks, wavelet neural networks, partial correlation analysis*

Changes of hydrological processes under climate change in the upper reach basin of the Yellow River

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Abstract: As the water tower of China, the upper reach basin of the Yellow River has been experiencing stresses of climate change and ecosystem degradation, which have resulted in less glacier/snow cover size, decreasing runoff and increasing evapotranspiration. The VIP ecohydrological dynamic model is applied to predict the hydrological processes in the upper reach basin of the Yellow River under the historical and future climate change with CIMP5 ISIMP projections. The ridge regression is used to analyse the contributions of climate change and vegetation changes to hydrological changes. The simulations are conducted with 1 km grid and hourly time step. The results show that there was a turning point in mid of 1990s, with runoff being increasing before 1995 and decreasing after 1995. The ET was intensified since 1980s, associated with an up-trend of vegetation productivity. The air temperature rising was the dominant factor to historical hydrological changes. Under the climate change scenarios, ET and runoff will increase noticeably till 2060s, then ET will keep quite stable and runoff will decline to 2090s; Under RCP8.5 annual ET and runoff will increase steadily from 310 to 430 mm and 70mm to 110 mm. Climate warming and precipitation increment are the main contributors to the hydrological changes under the climate change scenarios in 21 century.

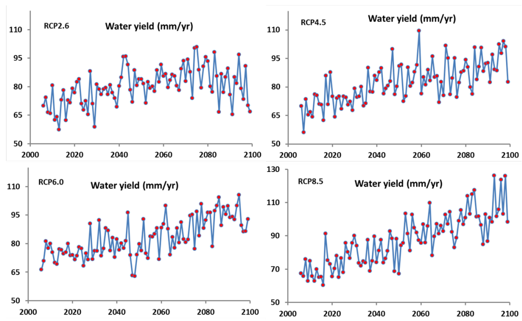

Figure 1. T he responses of water yield under RCP 2.6, 4.5, 6.0 and 8.6 scenarios

Keywords: *VIP ecohydrological Model, the Yellow River, climate change, hydrological changes*

Sediment load change observed by using both physically based model and statistical analysis

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Abstract: It is of great significance to quantify sediment load changing with erosion processes for improving the precision of soil loss prediction. rainfall simulation experiment was used as physically based model to observe sediment load and statistical analysis was used to explain sediment changing with erosion processes. Indoor rainfall experiments were conducted in 2 rainfall intensities (90 mm h^{-1} and 120 mm h^{-1}), four slope gradients (17.60%, 26.80%, 36.4%, 46.6%) and 2 slope lengths (5 m, 10 m). Erosion processes are divided into five stages. Results show that sediment yield is mainly sourced from rill erosion, contributing from 54.60% to 95.70% and the duration of which is extended by slope gradients. Sediment load and sediment concentration are significantly different along erosion stages, with the highest values in rill development stage (SIV). Surface flow velocities (interrill and rill) demonstrate less significant differences along erosion stages. Rainfall intensity increases sediment load in all stages, with up to 12.0 times higher when changing from 90 to 120 mm h^{-1}. There is an increasing trend for sediment load and sediment concentration with the rising slope gradient, however, fluctuations existed with the lowest values on 26.80% and 36.40%, respectively, among different treatments. Results from this study are important for validating and improving hillslope erosion modelling at each erosion stage.

Keywords: *Rainfall simulation, erosion experiments, rill erosion, interrill erosion, sediment load*

Temporal and spatial variation of precipitation in Nansha Islands, South China Sea

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Abstract: Precipitation is the single natural freshwater source in tropical reefs. In this study, Kriging interpolation, the sequential MK test and other statistical analyses were employed to detect variations in the annual precipitation in the South China Sea (SCS). The annual precipitation in the area ranges from 2000 mm to 3000 mm. The precipitation in the central area of the reef shows a two-peak pattern oriented NE-SW with a two category spatial distribution. The dendrograms based on between-groups linkage cluster method show the same two groups that HY and YS is one group and CG, DM, NX, ZB and MJ is the other group. Two to four different turning points of annual precipitation were found using MK test, especially relatively large one in 2003 (this was found in all the 7 artificial islands studied here). At the same time, the same trends of the five-year average precipitation were showed in seven islands. Compared with the first five years, the precipitation of the three consecutive five years shows that it is first decreasing, then increasing, and finally decreasing. Annual average precipitation at the next five-year stage in almost all islands is going up larger than the twenty-one-year average precipitation, which is essential for maintaining the reef ecosystem and drinking water for the permanent residents.

Keywords: *Precipitation, temporal and spatial variation, Mann-Kendall test, tropical reefs*

Using the DEMATEL method to identify key reasons for mathematics support

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Abstract: The Decision Making and Trial Evaluation Laboratory (DEMATEL) is considered as a useful and effective method for structural modeling which is comprehensively based on matrices. It is a commonly used method for modelling relationship between variables. DEMATEL has been applied in many areas such as project management, environmental engineering, social science, facility location problems and education for investigating relationship among variables. DEMATEL reveals the relationship and the severity of the effects of factors on each other. This method uses matrices and diagrams for visualizing the structure of complicated causal relationships.

There is an increasing concern worldwide about the level of mathematical skills that is necessary for students to pursue their studies successfully at universities. Many countries including Australia are currently increasing resources for improvement in the uptake of mathematics in secondary or high schools. In the short term however, there are numerous students enrolled in universities and other tertiary institutions who lack mathematical skills and, in some cases, severely. Since most university courses require some level of mathematics literacy, the need to find solutions to the problem has become important for many universities in the world. An effective way to address this is to engage students, by offering the study of mathematics at Mathematics Learning Support Centres. Fundamentally, learning support programs and especially in mathematics provide extra assistance to students in current enrolment in a university. In order to improve or maximise delivery of service at Mathematics Learning Support Centres, an assessment of the reasons for using the centres is required.

Ten reasons for seeking mathematics support were identified from literature review and interview with six experts comprising three mathematics learning advisers and students. The interrelationships among the reasons were considered in the application of DEMATEL method to determine the key reasons for seeking mathematics support. The DEMATEL method has identified that 'improving students' confidence in mathematics; helping students understand mathematics elements of course and reducing difficulty of solving mathematics problems as the top three important reasons for seeking mathematics help at a mathematics support centre at Central Queensland University (CQU).

Keywords: *DEMATEL, structural model, influence, mathematics support, reasons*

Optimization models to locate health care facilities

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Abstract: The rapid growth of population in cities and major regional areas, shorter length of stays in hospitals, ageing (and the desire of the elderly to stay longer in their homes), and traffic poses a challenge to health departments in meeting the demand for preventive, health center and emergency services. The changes in factors such as urbanization, demography and the rate of service utilization may affect the optimal distances or cost between patients and health care facilities. In addition, rapid population growth, increasing manmade and natural disasters seem to put increasing pressure on demands for timely health care.

There is a challenge in optimally locating health care facilities to enable the community to have good access to preventive, health center and emergency services. The location of health care facilities is an important aspect in health service delivery. It is therefore crucial for health care facilities to be located optimally to serve the community well. Facility location models have a greater importance when applied to the location of health care facilities because improper location will have a serious impact on the community.

The fundamental objectives of locating facilities can be summarized into three categories. The first category refers to those designed to cover demand within a specified time or distance. This objective gives rise to location problems which are known as the Location Set Covering Problem (LSCP) and the Maximal Covering Location Problem (MCLP). The LSCP seeks to locate the minimum number of facilities required to 'cover' all demand or population in an area. The MCLP is to locate a predetermined number of facilities to maximize the demand or population that is covered. The second category refers to those designed to minimize maximum distance. This results in a location problem known as the *p*-center problem which addresses the difficulty of minimizing the maximum distance that a demand or population is from its closet facility given that *p* facilities are to be located. The third category refers to those designed to minimize the average weighted distance or time. This objective leads to a location problem known as the *p*-median problem. The *p*-median problem finds the location of *p* facilities to minimize the demand weighted average or total distance between demand or population and their closest facility.

The objective of this study is to discuss the importance of the application of optimization models (maximal covering location and the *p*-median models) to locate health care facilities. We apply the *p*-median models and the maximal covering location models to real data from Mackay metropolitan area in Queensland, Australia. We compare the two models using the real data and with existing ambulance stations. The study shows that the *p*-median model gives a better solution than the maximal covering location model. We also noted that the results of the maximal covering location model depend on the pre-determined weighted coverage distance.

Keywords: *Optimization, models, healthcare, facilities*

2D chaotic flow in competitive exothermic-endothermic reactions

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Abstract: We study the effects of chaotic advection in a two-dimensional competitive reaction with an exother-mic reaction and an endothermic reaction and investigate the formation of the filament structure. In a chemical reaction, there are many processes and steps, even in the simplest reactions. By "lumping" these reactions together, a chemical reaction can be modelled using a fewer number of steps. As with any modelling exercise, the more steps that are included, the more complex the model is in terms of the number of system parameters, but this also allows a rich array of behaviour. The model considered here has two reactions, competing for the same fuel source, an exothermic reaction, which generates energy, and an endothermic reaction, which absorbs energy. An example of this type of reaction is the burning of ammonium nitrate in the context of emulsion explosives [Sinditskii et al., 2005].

In one dimension, these exothermic-endothermic reaction models can display complex behaviour. With a suitable initial temperature profile, a travelling reaction wave quickly develops, with three regions: ahead of the reaction where the fuel is unburnt and is at an ambient temperature, behind the reaction where the fuel has been consumed and is at a final burnt temperature and at the reaction front where the fuel is being consumed. Tracking the location of the reaction front, the system can exhibit a range of behaviour. Depending on the system parameters, the speed of the travelling wave can become constant, become oscillatory, with the possibility of period doubling behaviour, or the reaction does not propagate, leading to quenching. This was studied in detail by Sharples et al. [2012]. In two dimensions, similar behaviour can be found [Watt et al., 2019a].

By adding a mixing process to the combustion process, the system behaviour changes. The mixing added to the system was a blinking vortex flow. This flow models the outflow from a large bathtub with with two sinks that are opened in an alternating manner. This alternating flow has been shown to induce chaotic mixing [Károlyi and Tél, 1997]. Kiss et al. [2004] studied this flow as applied to a single step combustion process. It was shown that there is a critical mixing rate, above which the flame is quenched and the reaction stops. We extend this work by replacing the single step reaction with a two-step competitive reaction. As before, there is a critical mixing rate, above which the flame is quenched. In addition, we explore the sensitivity of the system parameters on the performance of the reaction, as measured by the average steady state temperature.

Keywords: *Combustion, chaotic mixing, quenching, laminar fluid flow, exothermic*

Optimal partitioning of photovoltaic modules on a curved solar collector

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Abstract: The Australian Technology Network (ATN) group of universities designed and built a solar car to participate in the 2019 Bridgestone World Solar Challenge. The car is powered by 29 photovoltaic modules on its top surface. To get a useful voltage from the solar collector, modules are connected in series. However, the power generated by a group of modules in series is limited by the module with the lowest irradiance. Irradiance depends on the angle between the sun and the cell normal, which is influenced by the curvature of the collector and the position of the sun relative to the car. If all of the modules were facing the same direction then each module would receive the same irradiance and there would be no "series mismatch" losses, but the solar panel is curved for aerodynamic efficiency.

Our challenge was to partition the modules into groups so that the energy generated by the solar collector is maximised during a six-day journey across Australia. We describe two methods for partitioning modules into groups. Our mixed-integer programming model provides optimal solutions for a single time instant, but can not solve the problem for the entire journey. Using a Cross Entropy Optimisation method, we were able to find solutions that were within 0.03% of optimal for a single time instant, and could also find good solutions to the six-day problem.

Keywords: *Solar energy, maximising efficiency, optimal partitioning, integer programming, cross-entropy optimisation*

Comparing the carbon footprints of food waste diversion options in Melbourne, Australia

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Abstract: The generation of food waste has been identified as a significant global environmental, economic and social problem. The UN Food and Agriculture Organisation has noted that over one third of food grown for human consumption is never eaten. In Australia, it has been estimated that over 7 million tonnes of food is wasted with the majority disposed of to landfills where it generates methane, a potent greenhouse gas. Recently, the Federal and the State/Territory Governments of Australia have launched the National Food Waste Strategy with the goal of halving food waste in Australia by 50% by 2030. While there is scope to reduce avoidable food waste through public education campaigns and the expansion of food rescue programs, there will still be a need to process unavoidable food waste so it can be diverted from landfill to beneficial uses.

In Australia, large-scale composting has been the main option for diverting food waste from landfill with a number of councils adopting a combined Food Organics - Garden Organics (FOGO) collection service for the residential sector. For sites with commercial or institutional kitchens, food waste diversion options have been limited in the past. With the increase in landfill disposal fees, more food waste diversion options are becoming available including onsite and offsite composting, onsite and offsite vermicomposting (worms), and anaerobic digestion (biogas). However, it is not clear from a greenhouse gas reduction perspective whether onsite options generate less carbon emissions with the absence of waste transport or does the economy-of-scale factor with larger facilities have a greater influence on carbon reduction. Alternatively, does energy recovery from biogas give a better carbon reduction outcome than the material recovery from composting and vermiculture.

To address the above research questions, a series of carbon footprints were generated for nine food waste diversion options relevant to metropolitan Melbourne including the landfill baseline scenario. The carbon footprints were calculated with regard to the following carbon burdens (1) and carbon benefits (2):

1. Transport emissions (diesel), biological emissions (methane & nitrous oxide) and operation emissions (electricity & diesel); and
2. Renewable energy generation, soil carbon sequestration, displaced fertiliser products.

This paper seeks to rank the modelled food waste diversion options on the basis of their carbon footprints. It is expected that over the next twenty years, grid electricity in Australia will be carbon neutral and the concept of circular economy with increased recycling of waste products, is mostly integrated into the Australian economy. With these predicted changes in energy form and material flows, the underlying assumptions of the carbon footprint parameters are expected to change significantly. This paper models the impact of these external forces on commercial food waste diversion over twenty year period onto the ranking of the carbon footprints to see if these policy drivers impact on the relative ranking of the considered food waste options. The modelling results for ranking food waste diversion options were counter-intuitive indicating that transport emissions were not significant and that larger facility-based options such as offsite composting and anaerobic digestion had similar carbon footprints to the onsite processing options.

Keywords: *Carbon footprint, circular economy, decarbonisation, food waste, Melbourne*

Stochastic processes in a discrete model of ground combat

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Abstract: Discrete models of combat are a rare part of the combat modelling literature. Our work introduces a stochastic version of a discrete ground combat based on Epstein theory featuring two adversarial sides, namely an attacker and a defender. Noticeably, the Epstein model of ground combat features an evolving battle front through a withdrawal mechanism to capture the connection between attrition and movement of the front historically prevalent in ground war. Our extension from the deterministic setting of the Epstein model to the stochastic setting is achieved by taking the exchange ratio of attackers lost to defenders to be a mean-reverting stochastic process. The extension of the exchange ratio to a stochastic process is interrupted to be the result of changing strategies and engagements by either side as well of the generally uncertainty of warfare known as the "Fog of War" upon the outcome of combat.

In the deterministic setting of our model, our toy numerical example results in an attacker victory. In the extension of the exchange ratio to a stochastic process, the attackers are no longer assured victory. However, the variations in the exchange ratio can be of benefit to the attackers in that they may achieve victory in a shorter combat duration and as a consequence suffer less attrition. Thus we interpret the stochastic process as introducing a "risk vs reward" scenario for the attackers where the risk is quantified through the volatility of the process. Our numerical simulations explore the shift in the outcome of combat for the attackers as they take on additional risk and more uncertainty is introduced into combat.

We observe the probability that the attacker is victorious, the time till victory when the attacker is victorious, and the remaining ground force strength of the attacking forces for varying volatility. Our results show that for increasing values of the volatility of the exchange ratio process, the probability of an attacker victory increases but the combat duration decreases and the remaining combat power of the attacker forces increases.

Keywords: *Combat models, stochastic processes, discrete models*

Multistage flow shop scheduling with bi-criteria objective using sequence dependent setup times

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Abstract: In many industrial setups, setup time on machines during the processing of given jobs in flow shop has great impact on the objective considered; hence the setups need to be taken separately during the process. Two types of setups exist in flow shop scheduling problem namely sequence-independent and sequence-dependent setup times. Scheduling of jobs with sequence-dependent setup times in flow shop scheduling is the most complicated case in the theory of scheduling. The main concern in this paper is the sequence-dependent setup time in which the setup time depends on the job type to be done and just completed. In this paper, a heuristic algorithm for solving bi-criteria flow shop problem with sequence-dependent setup times is proposed. The bi-criteria objective considered is the minimization of the operational cost of machines subject to minimum makespan in a flow shop whenever the setup times on machines are sequence-dependent. As the problem is NP-hard, the proposed heuristic algorithm finds the latest time at which the machines should start so as to reduce their operating time and hence the operational cost subject to minimum makespan. The problem discussed in the paper can easily be seen in the industrial setups where expensive machinery is in operation or it is difficult to start or stop the machines due to operations technical limitations. The proposed algorithm makes use of famous NEH algorithm with a new tie-breaking rule. The tie-breaking rule breaks the tie for sequences with equal makespan during the run of algorithm. The starting of machines at latest time reduces the operating time and hence the operational cost of machines. The proposed heuristic algorithm when applied to given set of data reduced the total operational cost of machines from 2166 units to 2040 units subject to minimum makespan 90 units thereby reducing the total cost of machines by 126 units. A numerical example is also given to substantiate the algorithm.

Keywords: *Scheduling, makespan, sequence-dependent setup time, operational cost, operational time*

Nitrogen removal in a cascade of four reactors employing the activated sludge process

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Abstract: The activated sludge process is the most widely used process for the biological treatment of domestic and industrial wastewaters. Wastewater treatment plants based on the activated sludge process are in widespread use in developed and developing countries. The activated sludge model number 1 (ASM #1) is an internationally accepted standard for activated sludge modeling. It describes nitrogen and chemical oxygen demand within suspended-growth treatment processes, including mechanisms for nitrification and denitrification.

We analyse the biological treatment of a wastewater when a cascade of four reactors is used. We assume that each reactor in the cascade has the same volume. Operating conditions are investigated in which the first reactor is not aerated whilst the last two reactors are aerated. The second reactor may either be aerated or not aerated. The process configuration includes one settling unit and one recycle unit. The settling unit is placed after the final reactor of the cascade. Part of its exit stream is wasted and the remainder is fed into the first reactor. The recycle unit is also placed after the final reactor of the cascade. The entirety of its exit stream is fed into the first reactor.

The performance of a wastewater treatment plant can be characterised by a number of process parameters. Here we consider the nitrogen concentration in the effluent stream leaving the treatment plant (TN_e). When the reactor configuration *includes* a settling unit this is defined by

$$\mathrm{TN}_e = S_{\mathrm{NO}} + S_{\mathrm{NH}} + S_{\mathrm{ND}},$$

where the state variables on the right hand are the concentration of soluble nitrate and nitrite nitrogen (S_{NO}), soluble ammonium nitrogen (S_{NH}), and soluble biodegradable organic (S_{ND}) respectively.

A combination of direct numerical integration and continuation methods are used to investigate the steady-state behaviour of the system. The governing equations were solved using both matlab (ode15s) and maple (lsode[backfull]). For continuation XPPAUT was used. We take the hydraulic retention time (HRT) as the bifurcation parameter, primarily allowing it to vary over the range $0 < \mathrm{HRT}\ (\mathrm{days}) \leq 1$. We investigate how the nitrogen concentration in the effluent stream depends upon the operation of the recycle units and the state of aeration in the second reactor.

Our results are summarised as follows.

1. When the second reactor is aerated the value of the recycle ratio that minimise the nitrogen concentration depends upon the value of the hydraulic retention time. There is a significant range of values for the hydraulic retention time over which the optimal performance is achieved by employing a 'moderate' recycle ratio.
2. When the second reactor is not aerated increasing the value of the recycle ratio always improves performance. Thus the recycle unit should be operated at the maximum attainable value of the recycle ratio.
3. If the maximum attainable value of the recycle ratio is 'low' then the second reactor should be aerated. If this value is 'high' then the second reactor should not be aerated.

Keywords: *Activated sludge, dentrification, modelling, nitrification, process modelling*

Evaluation of P-Delta instability in hardening oscillators using dynamical systems approach

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Abstract: Construction in earthquake prone areas is an expensive task, as the structural design warrants high material consumption. This is partly due to the fact that the seismic design philosophy is based on the concept of stability through energy dissipation. The energy dissipation is conventionally achieved by controlled *plastifi-cation* and *hysteresis* of the structural elements that require high quantities of reinforcements and sophisticated detailing, in both steel and concrete structures. Further, due to inherent uncertainty in the occurrence and the characteristics of earthquakes and also in the current simulation models, a conservative design is essential that can provide a sufficient margin of safety against failure. In the last two decades, however, there is a push towards developing *performance designs*. This new evolved philosophy of seismic design aims to quantify the uncertainties and the unknown aspects of the design to reduce the margins of safety, while sustaining equally high reliability. As a result, this leads to designs with low requirements of material consumption, thereby making them economic. Consequently, the complexity in the design process increases in almost every aspect, right from quantification of uncertainty by performing Monte-Carlo simulations to developing high-fidelity models that can incorporate all forms of non-linearity in the design. Moreover, to reduce the margins of safety, it becomes imperative to accurately estimate the point of failure or structural collapse capacity. However, currently under the Performance Based Earthquake Engineering (PBEE) framework, the collapse capacity is not evaluated corresponding the the actual dynamic instability in the structural system. Instead, it is estimated corresponding to subjective threshold values of engineering demand parameters, such as lateral deformation. Therefore, in the current paper, a novel-approach is presented that uses dynamical system theory for evaluat-ing dynamic instability in a structure that can be used to accurately estimate its collapse capacity. A *P-Delta instability* is the dynamic instability that occurs when gravity loads magnify the force demand due to the ge-ometry of the deformed structure, leading to high overturning moments on the base. This is widely studied under mainstream structural analysis. For simplicity, a single-degree-of-freedom (SDOF) system is studied. Therefore, the current work is targeted towards the structures that can be idealised as an SDOF system. The dynamic instability leading to "structural collapse" is defined when the real part of the dominant eigenvalue of the oscillator system becomes positive and remains positive until large deformations occurs. The current study uses harmonic excitations for evaluating dynamic instability and therefore acts as a precursor to a larger study aimed at evaluating mathematical instability in structures under the effects of seismic ground motions.

Keywords: *P-Delta instability, Dynamical system, Performance based earthquake engineering (PBEE) design, Collapse criterion*

Modification of interval arithmetic in modeling uncertainty of boundary conditions in boundary value problems

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Abstract: Nowadays, the finite element method (FEM) is the most known and the most commonly used method for solving boundary value problems defined exactly (without uncertainty). This method is based on the division of the domain into finite elements. These elements are connected to each other and produces a mesh. The second method, more recent, but also often used, is the boundary element method (BEM). This method is based on the division of the boundary only on the so-called boundary elements. This solution significantly reduces the amount of data required to solve the problem. Therefore, the amount of computer resources, needed to obtain a solution, is also significantly reduced. However, both FEM and BEM require a large number of points to define the shape of the boundary. It was the main reason to look for new methods. This is how the parametric integral equations system (PIES) appeared.

In this paper, the application of interval arithmetic for modeling uncertainly defined boundary conditions (in solving boundary value problems) is presented. In the literature, for solving such problems, different modifications of mentioned FEM and BEM methods appeared. Many different ways of modeling uncertainty have been used. However, the most important problem is to reduce the number of calculations. This is the main reason to choose interval arithmetic. Direct application of classical or directed interval arithmetic, into interval modifications of FEM and BEM methods, leads to significant overestimation. Therefore, it was decided to propose interval modification of the parametric integral equations system (PIES) method.

Recently, the PIES method has been thoroughly tested on examples of boundary problems, where input data were defined without uncertainty. During tests, the number of input data (necessary to define the problem) was always smaller (comparing with well-known methods). This also allows reducing the number of equations in the obtained system of equations. This gives a significant advantage (over other methods) in modeling uncertainty of input data.

The application of the interval PIES method resulted in a significant reduction of overestimation. However, obtained solutions (by direct application of interval arithmetic known from literature) are not exactly in line with expectations. Therefore, the modification of directed interval arithmetic has been proposed. It has been applied for calculations in the interval PIES method. The proposed method has been tested on examples of boundary value problems (modeled by Laplace's equation) with uncertainly defined boundary conditions. The uncertainty of boundary conditions has been defined as interval constant boundary conditions as well as interval linear function. Obtained solutions have been compared with the solutions of exactly defined (without uncertainty) PIES.

Keywords: *Uncertainty, interval arithmetic, boundary value problems, boundary conditions*

Computational design of molecularly imprinted electropolymer for selective recognition of nitrofurantoin

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Abstract: Nitrofurantoin (NFT) is a nitrofuran antibiotic previously employed in the treatment of diseases in aquaculture livestock such as fish and shrimp. The European Union completely prohibits the use of NFT in food due to its mutagenic and carcinogenic effects. The application of nitrofurans for livestock has also been banned in countries such as Australia, USA, Philippines, Thailand, and Brazil. However, NFT has found illegal use in many Asian countries.

Various methods have been utilized for NFT detection such as spectrophotometry, spectroscopy, liquid chromatography, chemiluminescence, photoluminescence, high performance liquid chromatography, and electrochemistry. Recently, novel molecularly imprinted polymers (MIPs) were developed for selective recognition of NFT. MIPs are synthetic materials which contain pre-designed cavities capable of recognizing the molecules of a target analyte (template). These pre-designed cavities complement the shape, size, and chemical functionality of the template. MIPs have the advantages of easy preparation, stability in harsh conditions, and low cost. Due to its lock-and-key mechanism, MIPs are ideal for selective and sensitive recognition of various templates such as drugs, amino acids, carbohydrates, proteins, nucleotide bases, hormones, pesticides, and co-enzymes.

While novel, previous MIPs developed for NFT detection are quite costly due to the additional raw materials used for synthesis, e.g. crosslinker, photoinitiator, dual monomers for copolymerization. The use of electropolymers can avoid the use of initiators and crosslinkers in the preparation of MIP while having control in the thickness of the deposited polymer film. To assist in the selection of electropolymer for MIP-based recognition of NFT, we employed computational chemistry to perform molecular simulations and evaluate the nature and energetics of the interactions present between the functional monomer and NFT in the pre-polymer complex. We applied density functional theory (DFT), an ab-initio quantum chemical calculation, to screen and determine the best functional monomer for NFT recognition. This study presents the results of computational screening with the optimum monomer selected from 4 low-cost precursors: 4-aminophenol (AMP), aniline (ANL), o-Phenylenediamine (o-PD), and pyrrole (PYR).

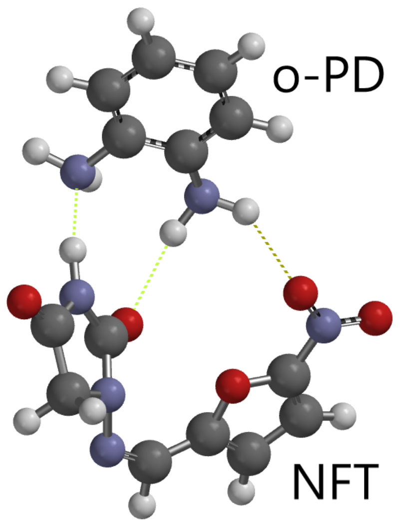

Figure 1. Simulated conformation of nitrofurantoin (NFT)-o-Phenylenediamine (o-PD) complex after optimization using density functional theory (DFT)

At 1:1 template-monomer molar ratio, PYR produced the most stable complex with NFT. PYR formed 1 stable intermolecular hydrogen bond with NFT and has the lowest interaction energy among the complexes (AMP > ANL > o-PD > PYR). However, with consideration to cost, o-PD is a better monomer than PYR with the former costing 50% less than the latter. Moreover, the results of our simulation show o-PD formed 3 stable intermolecular hydrogen bonds with NFT with interaction energy of only 10% higher than the NFT-PYR complex. A more stable complex was formed when the NFT-o-PD molar ratio was increased to 1:2.

Keywords: *Molecularly imprinted polymer, nitrofurantoin, density functional theory, interaction energy*

Investigating the value of upgrades to the Bega River and Richmond River Valleys

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Abstract: The Bega and Richmond River valleys are home to the relatively small water supply dams of Brogo and Toonumbar. Respectively they have an approximate capacity of 14GL and 11GL. There is potential to improve water supply reliability and to sell additional high security licenses on these systems by raising the dams. The challenge in assessing these options is in determining by how much to raise the dams and by how much would that increase the potential for additional high security licenses.

WaterNSW has developed eWater Source models for both valleys that can help answer these questions. These models are calibrated to as much observed data as is available and are then set up under current conditions to run for approximately 100 years using the available rainfall and evaporation data. From the results of these models, water security can be estimated for general and high security users, and results from changes to the system can be compared to the existing conditions to determine if conditions have improved or worsened with changes imposed on the models.

For both of these valleys comparing to existing conditions poses certain challenges, for Bega the general security users are unable to use all of their 14GL of entitlements in any years. This means that if the total general security entitlements were lowered, the percent per share entitlements would be improved without any practical impact on usage. The Richmond River valley faces a similar problem, in that if general security licenses were removed it would not have an impact on usage because it is so low. The difference between the two valleys is that for Bega there is no water available to increase usage, and for Richmond there is plenty of available water. Hence to compare potential options a baseline scenario was created that put these valleys usage at approximately their capacity and constrained the licenses to what could realistically be used.

A large number of combinations of options for adding high security entitlements and dam capacity were run and compared to the baseline scenario. This was done by running eWater Source via the command line and inputting the changes to the system with settings files passed to eWater Source. The percent per share entitlement and usage for high and general security users was recorded as output and processed to create an exceedance curve for the whole timeseries. Any option that had part of their exceedance curve below the baseline was determined to not be viable. These comparisons were made for over 300 potential combinations of additional dam capacity and high security entitlements for both dams and the results are a set of options that are viable.

For both systems the rate at which high security entitlement can be added to the system diminishes as the capacity of the dam is increased. Given this some “optimal” options were chosen that have the best additional high security licenses with the minimal amount of additional dam capacity. This will make them more viable when a cost benefit analysis is done on them to determine if they would be attractive options for customers. These “optimal” options were an additional 8GL dam capacity for Toonumbar and an additional 6GL of high security licenses for the Richmond River valley and an additional 7GL capacity in Brogo with an additional 4GL of high security licenses.

Keywords: *eWater Source, dam capacity, High Security Licenses, General Security Licenses, entitlement*

Modelling of Mid Lachlan System using eWater Source model

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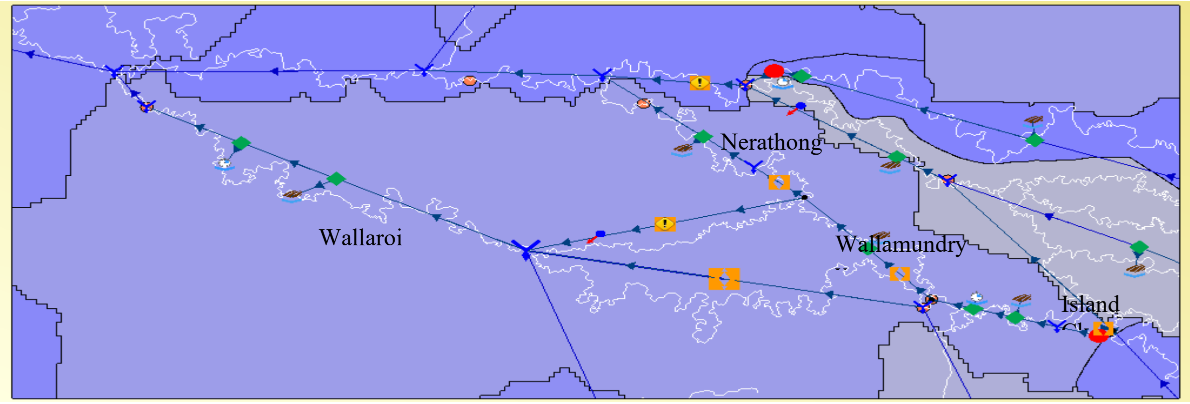
Abstract: The Lachlan River is an intermittent river that is part of the Murrumbidgee catchment within the Murray–Darling basin, located in the Southern Tablelands, Central West, and Riverina regions of New South Wales. Water is stored upstream in Wyangala and Carcoar dams and released downstream based on irrigation and environmental flows requirements. WaterNSW developed eWater Source Planning Model to assess strategic level assessment of potential infrastructure options to meet long-term level of service (LOS) objectives in regulated river. There were few challenges in modelling the Mid Lachlan System using eWater Source model given this effluent system has high transmission losses for delivery of water. The Mid Lachlan effluent system comprises of three creeks (Wallamundry, Wallaroi and Nerathong) and Island creek (this is the major effluent from Lachlan River System).

Transmission losses in the three creeks (Wallamundry, Wallaroi and Nerathong) were modelled as riparian vegetation evapotranspiration losses. The methodology for modelling evapotranspiration losses was based on advice and literature reviews provided by eWater and estimated via incorporating storage routing in the models. Two links one for rainfall and other for adjusted evaporative losses were modelled for this system. The flow width to use were provided by the river operators based on field data and experience. These widths were adjusted for Wallaroi creek as the modelled transmission losses were not found appropriate. The flow widths and channel depths were based on regulated flows and ratings (using the gauges on the three creeks). These ratings were adjusted for average recorded flows and depths in all the creeks and based on flow calibration. The transmission losses were based on unaccounted differences estimates as provided from past studies and data from river gauges. The model was calibrated for regulated flows in the system incorporating the transmission losses, river constraints, irrigation crop model and replenishment flows. The calibration showed good match with the gauged flows at number of locations within the Mid Lachlan system, also the transmission losses were comparable with the unaccounted difference estimates of about 15 GL/year. The modelled irrigation diversions also matched well with the recorded in the mid Lachlan system.

Modelled Annual Average Riparian Evapotranspiration Loss (ML/year) 1998-2016

	Length km	Losses ML/year
Wallamundry Creek	72.7	3,982
Wallaroi Creek	128	10,625
Nerathong Creek	34.7	908
Total Modelled	235.4	15,515
Unaccounted Differences estimates*		15,113

**Based on gauged flow differences*



Keywords: *Level of service (LOS), riparian Transmission loss*

Stability test for semi-active suspensions with base disturbance

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Abstract: Previous investigations by the authors (Storey et al. 2006; Storey et al. 2009; Storey 2011) indicate that controlled suspensions are capable of being “soft” (have a low damping rate) under placid conditions, and “hard” (high damping rate) when required to improve “tracking” (staying close to the middle of and avoiding hitting suspension limits). The question arises then whether such suspensions are safe. On the one hand, vehicles have had relatively high mandated suspension damping rates after Ralph Nadar (1972) famously found that cars with soft suspensions were prone to rollover. On the other hand, improved isolation and tracking should make suspensions more resilient to destructive harmonics.

The authors were curious to perform frequency analyses to compare fundamental linear controls against a simple piecewise linear system with controlled damping. This should be a good comparison of these systems since the frequency analysis of the linear systems is well known and very well understood.

For our analysis we compared three controls, two linear and one piecewise linear. The two linear controls were the standard linear quarter-car model (here called the “linear passive” control) and the well-known skyhook control. It has been claimed by Reichert (Reichert 1997, pp. 12-3) that studies “indicate that the skyhook control is the optimal control policy in terms of its ability to isolate the suspended mass from the base excitations.”. Whether or not this is the case, it is clearly superior to the passive. The main disadvantage of the skyhook is that it cannot be implemented in full by a controlled damper in a semiactive suspension. In the experiments described below, however, we investigated the simplest damping control possible, in which the damper is either on or off. The damper turns off when the force from the damper would add to the magnitude of the chassis’ vertical velocity. This control was called the switched skyhook, for reasons explained below. Such a control should be a good test of stability. The advantage of this control over the skyhook is that it can be implemented by a controlled damper, such as the relatively cheap magnetorheological damper.

Results of our numerical experiments show that the switched skyhook greatly improves on the linear passive. Figure 1 shows an example of transmissibility against frequency (as a proportion of the natural frequency). In this example each control has a damper with the same damping rate, $\zeta = \sqrt{2}$. As shown in Figure 1, the switched skyhook can greatly reduce the response amplitude (much less than one) at the resonant frequency, even with relatively high damping rates. It also provides a much smoother response at higher frequencies.

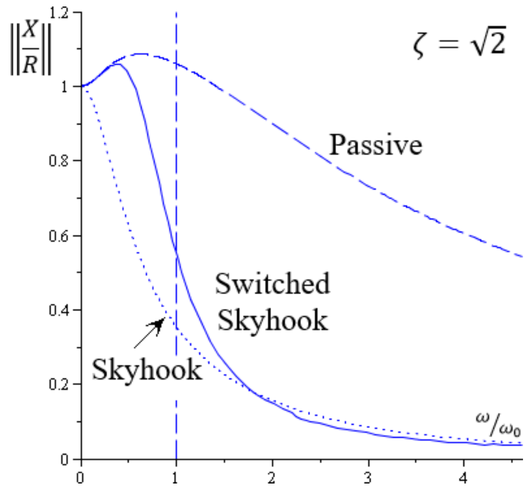

Figure 1. Comparison of linear passive, skyhook and switched skyhook.

Keywords: *Control, suspension, linear, skyhook, stability, frequency, damper*

T-splines and Bézier extraction in modeling shape of boundary in Parametric Integral Equation System for 3D problems of linear elasticity

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Abstract: T-splines are a generalization of NURBS surfaces. They retain all the properties of NURBS, but are increasingly considered as a better alternative. While the control points in NURBS lie in a rectangular grid of rows and columns, the control points in the T-splines may be incomplete. Moreover, T-splines allow for local insertion of new control points. The possibility of adding control points locally has many advantages. For the same geometric representation, T-splines require a much smaller number of control points than NURBS. Moreover, T-splines naturally eliminate the formation of gaps when connecting adjacent surfaces, which is a disadvantage of NURBS. Due to these advantages, T-splines have received increasing research attention in recent years.

In the present study, we will use T-splines in combination with the Parametric Integral Equation System (PIES) to solve 3D linear elasticity problems. PIES is a computational method for finding solutions to 2D and 3D boundary value problems and is based on the formal separation of the approximation of the boundary geometry from the boundary functions. The PIES formulation is independent from the physical representation of the boundary and, for any shape, it is always defined in the parametric domain and not on the physical boundary as in the traditional Boundary Integral Equations (BIE). As a result, the boundary can be described analytically in the form of mathematical functions directly included in the mathematical formula of PIES. In the previous studies, the 2D boundary could be defined by parametric curves such as Bézier, B-spline and Hermitte, whereas in the 3D case, we can apply parametric surfaces. These were flat Coons as well as smooth Bézier surfaces. The latter have particularly positive properties with respect to their flexibility and simplicity of implementation. This correlates with the fact that parametric curves and surfaces are widespread in CAD systems, e.g. NURBS. They have been intensively studied and modified into more effective variants such as hierarchical B-splines, PB-splines (Point based splines), T-splines, LR-splines (Locally refined splines) and PHT-splines (Polynomial splines over hierarchical T-meshes).

The aim of the paper is to extend the application of PIES to objects with boundaries represented by T-splines. In order to simplify the problem, we use a Bézier extraction mechanism for automatic conversion of T-splines surfaces into standard Bézier surfaces, previously used in PIES. The Bézier extraction transforms the T-splines basis functions into linear combination of standard Bernstein basis functions. Therefore, if we can transform the T-splines basis functions into Bernstein polynomials, this allows the T-spline surface to be replaced by a set of Bézier patches with the traditional parametric domain for each Bézier patch.

The reliability of the proposed approach is evaluated through numerical tests based on linear elastic problems. We show how to represent the boundary by T-splines and compare the accuracy of the results with known analytical solutions. We use a commercial T-spline plugin for Rhino from Autodesk to model and manipulate T-spline surfaces. The plugin also includes the Bézier extraction module that directly converts T-spline models to the appropriate ones constructed with Bézier surfaces. The presented examples confirm the applicability of the approach with high accuracy of the solutions.

Keywords: *Parametric Integral Equation System (PIES), T-splines, Bézier extraction, 3D linear elasticity*

Designing a new single-blade wind turbine using Computational Fluid Dynamics

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Abstract: PowerHouse Wind, a small business in New Zealand, designs, develops and manufactures micro wind turbines for use on lifestyle property blocks. Their current design is rated at 2 kW at a rated wind speed of 10 m/s and 315 rpm and has a cut-in wind speed of 3 m/s and a cut-out wind speed of 20 m/s. It has a unique one blade with teetering hub design that is specifically designed to cope with strong gusty winds. The wind turbine is soft-stalled to regulate power output with a variable rotation speed rotor that uses an electrical brake.

A combination of customer feedback as well as experience of New Zealand wind conditions has indicated a demand for a higher power rated turbine at 5 kW. For a small business it is not necessarily an easy task to develop a new product as facilities for testing and multiple design iterations are often not available in house and can be expensive to outsource. An additional complication in moving from a 2 kW to 5 kW rated turbine is a variation on the current design is not possible as different airfoil families are recommended to maximise power output.

How then does a small enterprise design, develop and test a new highly complex engineering product? A build and test approach is only appropriate if time and money are not constrained or is only used to test the final configuration. Using numerical methods has advantages over a physical approach as multiple designs can be evaluated relatively easily. Fortunately for PowerHouse Wind their current blade design has been previously evaluated through numerical simulation and observational methods. Valuable insight had been gained into not only the performance of the current blade design in terms of power output and stall on the blade but also into the appropriateness and practicalities of using such methods to aid in the design of a new blade. This previous work on the existing Thinair 102 blade compared different simulation methods; less resource intense two-dimensional methods; and a three-dimensional Computational Fluid Dynamics approach which is computationally expensive and requires expert users. It was found that when there was little stall on the blade the methods gave similar results. However, when stall was present on the blade, the two-dimensional methods overestimate the power output.

The design and development of the new blade therefore used a two-stage process. A two-dimensional blade design software, QBlade, was used to narrow the design envelope for the blade design in terms of position of the airfoil families, twist and chord length. Initial two–dimensional simulations were undertaken to ensure the new blade design generated reasonable lift (and therefore power) at the required optimum Tip Speed Ratio (TSR). A promising blade design was then selected for full three-dimensional CFD simulations across a range of appropriate wind speeds and rotor speeds. A detailed understanding of the relationship between the power output and stall behaviour with these parameters for the new blade design was established as a result that allowed PowerHouse Wind to evaluate the efficiency and effectiveness of this potential new blade design. This project has demonstrated that resource intensive state-of-the-art simulation methods such as CFD have a valuable role to play in new product design and development for small businesses. Care has to be taken to build on existing knowledge and be focused on what knowledge is required to progress the product development.

Keywords: *Computational fluid dynamics, wind turbine, stall behaviour*

Understanding the risk to operational success in contested environments

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Abstract: Operational success in the battlespace is influenced by a commander's ability to make the right decision at the right time thus seizing the initiative to proactively set or change the terms of conflict. By making faster decisions, friendly forces can gain the advantage of initiative in offensive operations, disallowing the enemy to recover from the initial shock of the attack. However, a commander has to balance the advantage of quick action with potential consequences and the risk to the force. Accurate intelligence can reduce uncertainty of the battlespace to facilitate decision-making but perfect intelligence is never a reality. Therefore, the decision to strike known targets in a highly contested environment relies on the commander's willingness to take some degree of risk. The payoff may be worth the risk if the value gained by destroying a target is higher than the threat imposed on friendly forces.

With limited self-protection capabilities, intelligence, surveillance and reconnaissance (ISR) assets operating in a high-threat environment tend to increase their standoff ranges in order to survive enemy defences. Hence, intelligence collection may be inadequate in providing sufficient battlespace awareness for the warfighters. More time for intelligence collection often enables an improved understanding of the battlespace, but not every targeting effort has sufficient time available to reduce the risk below the commander's acceptable threshold. Fighting against a risk-tolerant adversary, risk-averse commanders may seek to take a more defensive posture until timely intelligence is sufficient to support the planning and targeting processes.

Utilising actionable intelligence at the right time with the appropriate willingness to take risk is the key to successful offensive operations. In fact, there is no perfect solution that avoids making execution mistakes. Even if one has perfect intelligence, its usefulness will perish with time in a dynamic battlespace. Therefore, prioritising the collection efforts to the types of intelligence required for immediate decisions could be critical to offensive operations. For a fixed rate in intelligence collection, operational success may necessitate keeping the proper balance of target acquisition and threat assessments for force protection.

Using an abstracted agent-based combat model in a fictitious conflict, this paper seeks to evaluate the effect of a commander's hesitation in target engagement in terms of time delay in exchange for increased certainty in situation understanding. An exploratory analysis is performed to gain quantitative insight into the degree of risk to operational success resulting from proportional understanding of potential threats and elusive targets. Simple measures of performance are utilised to evaluate offensive and defensive power as an indication of the resulting effect. Initial results indicate that early warning of potential threats is as important as target acquisition to support offensive operations. Success in targeting could hinge on careful consideration to sensible uncertainty about the battlespace.

Keywords: *Operational success, contested environments, targeting, intelligence, risk*

Relational algebraic approaches to decision making under uncertainty

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Abstract: Uncertainty is so ubiquitous in most real world problems that understanding the fundamental nature of uncertainty is important. Stochasticity has been shown to be only one of the many dimensions of uncertainty. Uncertainty can be of many types and different methodologies for decision making are applicable in different cases. In cases where probability distributions of uncertain parameters cannot be ascertained with great confidence, robustness of strategies is more important than optimality and hence the robust optimization paradigm is more appropriate.

We present a simple ***polyhedral representation of uncertainty*** based on robust optimization that can be generated through specification of constraints or easily derivable from historical data with underlying uncertainty. Such representations are a convenient way to summarize large datasets and lead to tractable ways of comparing alternative scenarios or assumptions. We also present a ***set theoretic relational algebra*** to qualitatively compare these polyhedral models (polytopes) or alternative sets of uncertainty**.** The relational algebra arises because of the non-zero measure of these convex polyhedral objects - these are aggregates. We define the subset, intersection and disjoint relational algebraic operators to compare alternative scenarios or assumptions. An intersecting relationship between two polyhedral models based on assumptions means that there is commonality between the two assumptions. Similarly, if one is a subset of the other, then its underlying data is more specific than the other.

To facilitate analysis of a large number of such different scenarios with underlying uncertainty sets, we have also developed a novel database with facilities to store and perform such set theoretic analysis of alternative future scenario sets efficiently and easily through simple queries. We call our database as ***CMdB or Convex Model Database***. The database can be coupled to any decision support system to help in decision making and analysis under uncertainty. Hence, with our approach, it is easy to - quantitatively and qualitatively compare one set of future scenarios against another, resolve conflicting future estimations, optimize over such alternatives and relate the optimization outputs to the inputs. We can do this in a tractable manner with a wide variety of constraints and assumptions about the future. We show this in the paper with our examples from supply chain and transportation systems.

Keywords: *Decision making under uncertainty, Convex modelling, convex model database, decision support systems*

Operations Analysis Support to the Combined Maritime Forces (CMF)

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Abstract: The Combined Maritime Forces (CMF) is a 33 nation naval partnership, which exists to promote security, stability and prosperity across approximately 3.2 million square miles of international waters, which encompass some of the most strategically important maritime areas in the world, including choke points at the Suez Canal, Bab al Mandeb, and the Strait of Hormuz. The CMF Area of Operation (AOO) contains 60% of global fossil fuel reserves and 30% of global oil production facilities. Close to a trillion dollars of annual trade moves through the region onboard approximately 70,000 vessels. Freedom of navigation and free flow of commerce in the region are threatened by terrorism, illicit networks and piracy. The CMFHQ is situated in the Kingdom of Bahrain and consists of three Combined Task Forces (CTF), CTF 150 (Maritime Security), CTF 151 (Counter Piracy) and CTF 152 (Arabian Gulf Maritime Security). The ADF provides support to the international effort through Operation MANITOU.

In the context of CMF's Maritime Security Operations, understanding typical behavior patterns for maritime vessels operating in the AOO provides the opportunity to optimize employment of CMF assets based on historically observed trends and resultant predicted future behaviors (e.g. positioning vessels along known drug smuggling routes).

As part of the ADF support to CMF, DST Group deploys a suitably trained and prepared Operations Analyst on a six monthly rotation. The role of the Operations Analyst within CMF is ultimately to improve the effectiveness of the HQ through the application of analytical rigour. The OA tasking ranges from long term strategy and assessment such as the CMF Annual report and Measures of Effectiveness development, through to operationally focused activities such as seasonal trend analysis and effectiveness of counter narcotics operations. One critical activity is supporting Focussed Operations by providing advice to the Commander regarding asset allocations based on historical data analysis.

Between October 2018 and May 2019, the author deployed to CMF as an Operations Analyst. During this time, there was a significant increase in communication and interoperability with non-CMF nations which has led to closer coordination and cooperation across the AOO. Analysis of the data sourced from Canada's Unclassified Remote Sensing Situational Awareness (URSA) Satellite system helped to mitigate periods of low force flow and assisted greatly in planning operations and in several successful interactions at sea.

Analysis of other data sets (such as Sea Vision, Marine Traffic, Naval Cooperation and Guidance for Shipping, United Kingdom Marine Trade Operations as well as Observations from ships) indicated a clear correlation between the Weather, Force flow and Illicit Activities in the AOO.

This presentation will discuss the various forms of analysis and visualisation techniques (including statistical correlation and geospatial analysis) conducted during the author's deployment. The outputs of this analysis contributed to CMF operations which resulted in 4,434Kg of heroin, 55,508Kg of hashish and 9 Kg of methamphetamine being seized by warships from 5 different countries, resulting in the denial of US$75M to terrorist and criminal networks across the region.

Keywords: *Maritime security, counter-piracy, Gulf Maritime Security, Operations Analysis*

Modelling time decay in uncertain implication rules of evidence theory with a focus on cyber attacks

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Abstract: Key to a successful organisation is the ability of its cyber security to respond in a timely manner. Hence, speed with regards to having up-to-date knowledge of the system state is paramount. However, this knowledge may not always be perfect or complete. A way of quantifying this uncertainty is through the use of a reasoning under uncertainty framework. One such framework is the theory of belief functions such as evidence theory or Dempster-Shafer theory. It has connections to other frameworks such as probability, possibility and imprecise probability theories. But, in cyber security, uncertainty modeling is not enough. A ubiquitous problem present in this domain is in modeling cyber attacks so that causal statements that follow a kill chain (a well-known paradigm to describe the phases of a cyber attack) can be accurately represented. One way this could be done is through implication rules. More precisely, a law of implication is a type of relationship between two statements or sentences. Hence, Dempster-Shafer Theory which incorporates implications rules with respect to time would be desirable in the cyber domain as a way to model cyber attacks. The aim of this paper is to be able to model the different stages of a cyber attack using Dempster-Shafer Theory that also incorporates a time parameter. Examples are also provided to illustrate the novelty of this work.

Keywords: *Cyber security, Dempster-Shafer Theory, time-decay models*

A protocol for selecting a rule of combination for fusion of imprecise cyber sensor data

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Abstract: There does not seem to be a day that goes by where there is not news of a new and potentially catastrophic cyber attack infecting computers and networks. In addition, even if it were possible to fully list all possible attacks, cyber sensors might not have the fidelity to correctly identify the type of attack. To further complicate things, it is more likely that these sensors must not only contend with quickly detecting known threats but also attacks which are new and unforeseen. Hence, modelling techniques are needed that will help take into account the possibility that the full possible range of potential threats may not be precisely represented as well model ambiguity and partial information. Dempster-Shafer Theory is one such framework because it not only deals with imprecision but there are also different combination rules which can be used depending on whether it is assumed that the full set of possible outcomes is known or not. Here, a protocol is provided to help the analyst select which combination rule should be used based on the assumptions he or she is making. The importance of these assumptions is illustrated through an example to show how results can vary according to the rule chosen.

Keywords: *Cyber security, cyber sensors, Dempster-Shafer Theory*

Bayesian Statistics in Operations Research

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Abstract: Operations Research (OR) emerged during World War II in response to the numerous and challenging problems involving probability and uncertainty. These problems were primarily addressed through the decision-theoretic framework developed by Neyman, Pearson, and Wald (NPW). The NPW framework continues to be the dominant statistical framework used by the OR community, in contrast to the physical sciences (Cousins 1995), statistics (Efron 1986), and machine learning communities (Breiman 2001), where Bayesian methods have been adopted to a far greater extent. We argue a deeper appreciation of Bayesian statistics would benefit the OR community.

The NPW and Fisherian approaches to statistical inference focus on the long-run properties of the inferences and decisions. They rely on a mixture of principles and techniques such as unbiased estimation, fixing the coverage of confidence intervals, control of the Type I (false positive) error rate, and so forth. Despite the desirability of these properties, they often have unintended and undesired side effects. For example, unbiased estimators do not exist in many situations, and when they do, they can exhibit high variance and non-sensical answers (Bernardo 2009). Similarly, confidence intervals can attain a desired level of coverage without satisfying other, equally important, aspects of inference. The canonical example is the confidence interval that is the real number 95% of the time, and is otherwise the empty set (Gelman 2013).

Bayesian statistics is better suited for many OR problems. Inferences are unaffected by stopping rules which is useful when experiments cannot be precisely designed or controlled, the methods can naturally incorporate missing data or other constraints into the model, and the Bayesian version of confidence intervals, credible intervals, are more easily interpreted by non-specialists (Gelman 2013). Of course, Bayesian methods have their own limitations that need to be understood by the OR community. Bayesian methods usually lack the guarantees found in the NPW framework, they require the specification prior distributions, and often require sophisticated numerical calculations.

In this talk, we will compare and contrast the frequentist and Bayesian approaches to statistics. We will highlight the value that Bayesian statistics can bring to Operations Research, and show that modern practices like cross-validation and sensitivity analysis can alleviate some concerns about prior distribution or model misspecification.

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Keywords: *Bayesian statistics, probability, uncertainty*

Uncertainty quantification in classification problems: A Bayesian approach for predicating the effects of further test sampling

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Abstract: The use of machine learning techniques in classification problems has been shown to be useful in many applications. In particular, they have become increasingly popular in land cover mapping applications in the last decade. These maps often play an important role in environmental science applications as they can act as inputs within wider modelling chains and in estimating how the overall prevalence of particular land cover types may be changing.

As with any model, land cover maps built using machine learning techniques are likely to contain misclassifications and hence create a degree of uncertainty in the results derived from them. In order for policy makers, stakeholder and other users to have trust in such results, such uncertainty must be accounted for in a quantifiable and reliable manner. This is true even for highly accurate classifiers. However, the black-box nature of many machine learning techniques makes common forms of uncertainty quantitation traditionally seen in process modelling almost impossible to apply in practice. Hence, one must often rely on independent test samples for uncertainty quantification when using machine learning techniques, as these do not rely on any assumptions for the how a classifier is built.

The issue with test samples though is that they can be expensive to obtain, even in situations where large data sets for building the classifier are relatively cheap. This is because tests samples are subject to much stricter criteria on how they are collected as they rely on formalised statistical inference methods to quantify uncertainty. In comparison, the goal of a classifier is to create a series of rules that is able to separate classes well. Hence, there is much more flexibility in how we may collect samples for the purpose of training classifiers. This means that in practice, one must collect test samples of sufficient size so that uncertainties can be reduced to satisfactory levels without relying overly large (and therefore expensive) sample sizes. However, the task of determining a sufficient sample sizes is made more complex as one also need account for stratified sampling, the sensitivity of results as unknown quantities vary and the stochastic variation of results that result from sampling.

In this paper, we demonstrate how a Bayesian approach to uncertainty quantification in these scenarios can handle such complexities when predicting the likely impacts that further sampling strategies will have on uncertainty. This in turn allows for a more sophisticated from of analysis when considering the trade-off between reducing uncertainty and the resources needed for larger test samples.

The methods described in this paper are demonstrated in the context of an urban mapping problem. Here we predict the effectiveness of distributing an additional test sample across different areas based on the results of an initial test sample. In this example, we explore the standard frequentist methods and the proposed Bayesian approach under this task. With the frequentist approach, our predictions rely on assuming fixed points for unknown parameters, which can lead to significantly different results and no formalised way to distinguish between them. In contrast, a Bayesian approach enables us to combine these different results with formalised probability theory. The major advantage of this from a practical perspective is that this allows users to predict the effect of an additional test sample with only a single distribution whilst still accounting for multiple sources of uncertainty. This is a fundamental first step when quantifying uncertainty for population level estimates and opens up promising future work in for the prorogation of uncertainty in more complex model chains and optimising the distribution of test samples.

Keywords: *Uncertainty quantification, land cover mapping, Bayesian, sampling strategies*

Inventory Control with Partially Observable States

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Abstract: Consider a retailer who buys a range of commodities from a wholesaler and sells them to customers. At each time period, the retailer has to decide how much of each type of commodity to purchase, so as to maximize some overall profit. This requires a balance between maximizing the amount of high-valued customer demands that can be fulfilled and minimizing storage and delivery costs. Due to inaccuracies in inventory recording, misplaced products, market fluctuation, etc., the above purchasing decisions must be made in the presence of partial observability on the amount of stocked goods and on uncertainty in the demand. A natural framework for such an inventory control problems is the Partially Observable Markov Decision Process (POMDP).

Key to POMDP is that it decides the best actions to perform with respect to distributions over states, rather than a single state. Finding the optimal solution of a POMDP problem is computationally intractable, but the past decade has seen substantial advances in finding approximately optimal POMDP solutions and POMDP has started to become practical for many interesting problems.

Despite advances in approximate POMDP solvers, they do not perform well on most inventory control problems, due to the massive action space (i.e., purchasing possibilities) of most such problems. Most POMDP-based methods limit the problem to a one-commodity scenario, which is far from reality.

In this paper, we apply our recent POMDP-based method (QBASE) to multi-commodity inventory control. QBASE combines Monte Carlo Tree Search with quantile statistics based Monte Carlo, namely the Cross-Entropy method for optimization, to quickly identify good actions without sweeping through the entire action space. It enables QBASE to substantially scale up our ability to compute good solutions to POMDPs with extremely large discrete action spaces (in the order of a million discrete actions).

We compare our solution to several commonly used inventory control methods, such as the (s, S) method and other state-of-the-art POMDP solvers. The results are promising, as it demonstrates smarter purchasing behaviors. For instance, if we combine maximum likelihood with the commonly used (s, S) policy, the latter policy is very far from optimal when the uncertainty must be represented as a non-unimodal distribution. Furthermore, the state-of-the-art POMDP solver can only generate a sub-optimal policy of always keeping the stocks of all commodities at a relatively high level, to meet as many demands as possible. In contrast, QBASE can generate a better policy, whereby a small amount of sales are sacrificed to keep the inventory level of commodities with expensive storage cost and low value, to be as low as possible, which then lead to a higher profit.

Keywords: *Inventory control problem, multi-commodity, partially observable Markov decision process, on-line POMDP solver*

The value of optimal stochastic control when operating hybrid ground source heat pump systems

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Abstract: Ground source heat pump systems provide heating and cooling for buildings by pumping heat between the air inside the structure and the nearby ground via a fluid loop contained in a bore hole. These systems can be hybridized with solar thermal collectors and water storage tanks. The collectors and tank provide for greater water entry temperature to the heat pump (leading to higher energy efficiencies) as well as ground-heat recharging. The energy efficiency of these systems is such that there are lower operating costs compared to conventional heating and cooling systems based on gas, oil or electrical energy, and major reductions in greenhouse gas in cases where the carbon intensity of conventional energy supplies is high.

The operating costs of a hybrid ground source heat pump (HGSHP) system are dependent on the schedules of building air cooling/heating, storage tank heat accumulation/deaccumulation, ground loop heat injection/extraction, and (where installed) the use of auxiliary space heating/cooling and/or storage-tank heating to deal with demand extremes. These schedules are formed explicitly or implicitly by control systems, and the scheduling decisions are always made in the presence of significant uncertainty about near-future ambient temperatures, solar radiation, the activities of building occupants, and other energy sources and losses. The simplest control method for HGHSP, in heating mode, is by way of *set-point control* where heating of building air occurs whenever the ambient indoor temperature drops below the temperature set-point, and where the extraction of energy from energy sources are also governed by temperature setpoints of the sources. Beyond set-point control there are control approaches of various complexity, practical applicability, and mathematical interest. *Deterministic Model Predictive Control* (DMPC) based on linear programming and using either a single deterministic forecast or a small number of likelihood-weighted deterministic scenarios is one such approach, and another is *stochastic optimal control* (or somewhat synonymously, real options methods or approximate dynamic programming) using Monte Carlo simulations, control randomisation, and the application of linear regression or machine learning techniques to relate system states and optimal control values over the decision horizon.

Our aim is to evaluate the performance of set-point, DMPC and stochastic optimal control approaches to a HGSHP system in heating mode. In doing this we utilise a mathematical model of a HGSHP system that has been validated by data gathered from a real-world HGSHP system in suburban Melbourne, and this same data is used to provide realistic dynamic building heating and cooling demands in our numerical experiments. These demands vary hour-to-hour and day-to-day according to predictable factors such as ambient temperature and time of day, as well as random factors associated with the utilisation of the building by its inhabitants. Our experiments show that DMPC is a poor method of system control when assessed under real world variability. It is clearly outperformed by the much simpler set-point control method. By contrast, stochastic optimal control approximately halves the cost optimality gap between set-point control and a lower bound obtained by applying DMPC to more accurate prediction of future. This equates to around 4% of the total operational cost. These savings mainly stem from the extended use of auxiliary heating using grid-sourced electricity being necessary when using set-point control. The auxiliary heating is required when the total heating demand is high, to avoid the internal air temperature dipping below a lower limit. The stochastic optimal control method anticipates the heating demand spikes, and pre-heats the building spaces prior to the demand extreme.

Keywords: *Building energy efficiency, ground source heat pump, stochastic optimal control, regression Monte-Carlo*

Visual analytics, narrative visualisation for data farming of modelling complex warfighting

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Abstract: This work focuses on three aspects: (a) Visual Analytics which is science of analytical reasoning facilitated by interactive visual interfaces, (b) Narrative Visualisation to explain complexity of simulation outcomes and (c) use of Artificial Intelligence to predict various patterns and behaviours in multi-dimensional data sets to support storytelling for decision making. All of those are applied on the outcomes of simulations of complex warfighting for Joint Operating Concept Analysis. The agent-based simulation JFOrCE that was developed by DST Group is used to provide the simulation data.

Visual analytics: Data analysis and visualisation support the decision-making process by enabling analysts to make sense of the large amount of data generated from data farming. It is deployed through effective use of multi-modal visualisation systems, and successfully applied to multi-dimensional data using visualisation approach. This approach graphically illustrates and spatially interacts with the data, enabling decision makers to understand, explore and gain meaningful insights from the outcomes of complex simulations and data capture. The project outcomes showcase novel opportunities to facilitate data exploration with a human-in-the-loop using combination of machine learning, high performance graphics and interactive visualisations, and combining the strengths of human intuition with the power of computing to enhance decision making process. Visual analytics toolbox is developed to support construction of narrative visualisation, and allows to explore data through parallel coordinate graphics, regression models plots and partition trees.

Narrative visualisation: With the visual analytics toolbox allowing the visual exploration of the multi-dimensional JFOrCE data, a necessity arises to allow analysts and decision makers to create a coherent story by connecting facts and annotating relations in various graphs showing the data from different viewpoints. This type of analysis allows the communication of analysis steps and thought processes of the analysts and enables an effective way of presenting data by using narrative visualisation to facilitate the conveyance of context to a broader audience, especially decision makers. The visualisation module is integrated in the visual analytics toolbox, incorporating well-established methods, such as animated transitions between data graphs, brushing and linking (i.e. connecting multiple visual representations of the same data through selection of a subset), highlighting by zooming or subset selection, and annotating regions of interest. The modules implement the function to capture these methods in a series of scenes, creating a comprehensive story arc with interactive elements.

Outcomes/Implications: The decision-making process that is designed in this project aims to cover a full pipeline of visual analytics and narrative visualisation in order to provide an easy-to-use toolkit for users to analyse data coming from the agent-based simulations such as JFOrCE. The visualisation is built on the top of a production-grade software toolkit for shared visualisation systems, the High-End Visualisation System (HEVS) enabling content to be run transparently on a wider range of platforms with fewer compatibility issues and dependencies. Content can be transferred easily from large screens (including cluster-driven systems), multi-wall displays and head-mounted displays (including virtual reality and augmented reality). This common framework provides a unifying approach to visual analytics, visualisation and connected computing as a service, and in the context of this project, delivers universal solution that can be also applied to vast range of data.

Conclusion: During the conference, we will demonstrate the whole developed workflow: starting from data, constructing multi-dimensional visualisations, making sense of data using narrative visualisation, that eventually lead to informed decision making in domain of data farming, modelling of complex warfighting.

Keywords: *Visual analytics, narrative visualisation, data analytics, data farming, simulation and modelling*

Evaluating a virtual human storyteller for improved decision support

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Abstract: Defence and security organisations face increasing challenges to maximise the real-time integration of data and information for improved decision making. This is particularly true in applications of human-machine teaming. These teams create complex interaction environments for human operators that integrate autonomous systems, multi-modal displays, and information streams at differing temporal scales. Examples of these complex environments can be seen in simulation pilots operating in large scale synthetic training scenarios, and operators of multi-unmanned aerial vehicle (multi-UAV) systems. In both these cases, an individual must perform a primary task (directing simulated or real entity behaviour), whilst simultaneously following a pre-defined scenario plan. On top of this, emergent information, with varying levels of uncertainty, must be acted on or ignored as appropriate. Additional contextual information may also be required such that these actions can occur with an understanding of broader contextual factors. The efficiency with which this primary, planned, emergent, and contextual information is presented underpins decision support and superiority in increasingly complex military contexts. In this research, we evaluate the use of storytelling via a virtual human to deliver complex geo-spatial conflict briefing information.

The role of virtual humans in information delivery is an area of active research. At the intersection of education, psychology, and computing, the development of effective virtual humans is a difficult task. Many factors contribute to their effectiveness, including cognitive loading associated with different forms of multimedia, as well as the design and features of the virtual humans themselves. Further complicating this is the inherent learning abilities and inclinations of individuals, and their underlying preferences for different learning and information delivery approaches.

Figure 1. DST Virtual Human Storytelling system

In this research we conducted an initial evaluation of the delivery of narrative content using the Defence Science and Technology (DST) Virtual Human Storytelling system (Figure 1). An experimental methodology was adopted, using a between-subjects design. A total of 87 participants viewed a 3-minute multimedia video on a hypothetical conflict scenario in a fictious location that included details of actors in the conflict, actions occurring between these actors, and the geographic location. Three experimental conditions were used: a control group with the scenario delivered using text and images; a virtual human condition, with the scenario delivered using an animated avatar, synthesised speech, and images; and an audio condition, with the scenario delivered using synthesised speech and images. Preliminary analysis of the results suggests differences in performance on the information recall task, with participants in the virtual human group recording a greater range of, and higher maximum, scores. While simple between group comparisons of mean scores were not statistically significant, the higher maximum recall scores for participants in the virtual human group are promising. Directions for future work are also outlined, including incorporation of a measure of real-time cognitive load to isolate learning content for optimum delivery of information at a more granular level.

Keywords: *Decision support, virtual humans, simulation, cognitive load, storytelling*

EXTENDED ABSTRACT ONLY

Navy Mission Planner

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Abstract: Navy Mission Planner generates logistically supportable combatant employment plans to maximize mission accomplishment. An area of operations is parceled into homogeneous regions, and day-by-day there are missions located in these regions (e.g., antisubmarine warfare, air defense, maritime interdiction, etc.) requiring combatants. Some missions may necessitate that other missions be assigned simultaneously in the same region (e.g., mine clearance may require air defense protection), and some prerequisite missions may need to be completed in advance (e.g., antisubmarine warfare before marine interdiction operations). Bundles of inter-dependent missions are called mission packages. Each combatant can be operated in one of its alternate combined mission categories, wherein it can complete multiple missions simultaneously, albeit with varying effectiveness depending on the mission set undertaken and readiness condition of the combatant. Our planner can support logistic ship operations in concert with combatant plans. Logistic ships may need combatant escorts that can be shared region-wide, or must keep close. A typical scenario involves about 20 regions, a 24-day planning horizon, 700 missions, and 30 ships. Planner solutions help assess both combatant- and logistics-force capability.

Keywords: *Operational planning, operational logistics*

Scheduling combat logistic force replenishments at sea for the US Navy

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Abstract: The Replenishment at Sea Planner (RASP) is used by U.S. Navy to plan voyages by its Combat Logistics Force (CLF) ships to minimize the delivery cost of fuel and goods during peacetime and maximize deliveries in conflict. CLF shuttle supply ships deploy from providers (tankers or ports) to rendezvous with underway U.S. combatants and those of coalition partners. The overwhelming commodity transferred is fuel, ship-to-ship by hoses, while other important packaged goods and spare parts are highlined, or helicoptered between ships. The U.S. Navy is organized in large areas of responsibility called numbered fleets, and within each of these a scheduler must promulgate a daily forecast of CLF shuttle operations. The operational planning horizon extends out several weeks, or as far into the future as we can forecast demand. We solve RASP with integer linear optimization and a purpose-built heuristic. RASP plans Replenishment-at-Sea (RAS) events with four-hour (Navy watch) time fidelity. For six years, RASP has served two purposes: (1) it helps schedulers generate a daily schedule and animates it using Google Earth, and (2) it automates reports and command-to-ship messages that are essential to keep this complex logistics system operating.

Keywords: *Operational scheduling, operational logistics*

New Investments to Risk Options (NITRO) – a portfolio analysis and optimisation tool to support force design investment decisions

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Abstract: Australian Department of Defence aims to implement an economic approach when making major decisions about investment in future Defence capability. To achieve this, force designers need a tool for developing portfolio options. This would aid analysis, selection and scheduling of new initiatives in the form of gaps and opportunities (G&O) and existing Integrated Investment Program (IIP) projects to maximise overall Australian Defence Force capability under fiscal constraints.

As part of support to the current force design activities in Defence, DST has developed a model for optimising investments in new capability options presented in the Defence Capability Assessment Cycle (DCAP) and earlier force design activities. The model maximises the value of a collection of chosen capabilities subject to remaining within future budget year ceilings. The budget ceilings are provided by current investment projects, known as risk options, which can be traded off against the new capability options. Formally the model is a multiple knapsack problem, but the solution approach is via Integer Linear Programming rather than a dedicated knapsack algorithm.

The model, called NITRO (New Investments to Risk Options), has been developed in Microsoft Excel (Microsoft Office Professional Plus 2010, Version 16.0.4849.1000) using a commercial linear programming solver, Lindo What'sBest! (16.0.2.2). The MS Excel solution was progressed because of a need for quick and flexible tool development, deployability into user syndicates, and to provide military analysts with a familiar interface in which they could easily enter and manipulate data.

The tool lists the total collection of new capability options and existing risk options (i.e. current projects) under consideration. Capability options have a value depending on when they start, and risk options have their current values. Values have been assigned by subject matter experts using multi-criteria decisions analysis (MCDA) methodologies. Users can nominate capability options and/or risk options to include in the portfolio and in addition, if desired, can nominate preferred starting years of capability options. Other capability and risk options are selected by the solver based on their value, annual budgets and the annual budget ceilings. The tool has a number of checks and balances to guide users in maintaining feasible solutions. Logical and scheduling dependencies of capability and risk options can be defined by users to constrain their selection within the portfolio.

The model and tool has been used in a set of syndicates comprised of senior Defence decision makers as part of the current Force Structure Plan 2019 (FSP 19) activities, with each syndicate pursuing a different theme of capability investments. This generated a number of portfolios for further strategic testing and experimentation.

Keywords: *Force design, investment portfolio, portfolio optimisation, project scheduling, knapsack algorithm*

A New Model for Topical and Thematic Analysis to Support Force Design Decision Making

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Abstract: In Force Assessment activities across Defence, many documents containing essential information are generated. There is an increasing need to carry out a topical or thematic analysis of these documents in a fast and meaningful way for supporting decision making in Force Design. Several commercial tools such as WordStat, and Alteryx were tried recently, and found to be good for general purpose text analysis, such as text sentiment analysis with the embedded dictionaries. However, it appears to be difficult to tailor the tools to the particular needs of Defence. For instance, it is difficult to deploy a domain-specific dictionary for carrying out a tailored analysis for special requirements. Additionally, n-gram textual analysis functions in these tools are often very limited or unavailable. Visualisation could also be problematic since many special visualisation needs are seldom provided by commercial tools. To address these issues, we have researched a more effective way for mining text with domain lexicons and developed a model to measure the relevancy of words/phrases/documents with respect to the given domain lexicons that are of special interests to particular stakeholders.

As distinct from the widely used monotonic approach (term frequency and inverse document frequency(TF-IDF) method to get the sentiment of a corpus, the model developed in this research computes the words/phrases/document relevancy according to the size of the cleaned documents (no stop words, numbers, and etc.), weight of the words in a domain lexicon, and TF-IDF. The word "relevance" as a measure has been a research topic in information science for a long time and has numerous definitions. In this research, we use the term relevancy as a measure, which is defined as the extent a query or queries (a word/phrase/document) are related to the particular domain of interests represented with a set of domain lexicons or a set of words that are of special interest to stakeholders.

The focus of the research is on finding the representative words, phrases, paragraphs, or documents via mining the entire corpora using the calculated relevancy. The domain lexicon is developed using an unsupervised machine-learning algorithm and a supervised machine learning algorithm that considers SMEs' inputs.

Our experiments with a corpus of Cyber-Security academic papers show the model provides richer information than those commonly used to help stakeholders identify topical and thematic words that are of interest. Our experiments with SMEs' textual output of Force Assessment activities also show the model helps identify the topics and themes of the text documents more effectively. An example of the comparison of outputs of our model with that of Wordstat is shown in the figure below. We can see the words and phrases identified using our model are more relevant to the themes of the papers used in the experimentation. Further research will improve the model and develop an application that presents the recommended topical and thematic sentences or paragraphs to the special interests of stakeholders to support decision making in Force Design.

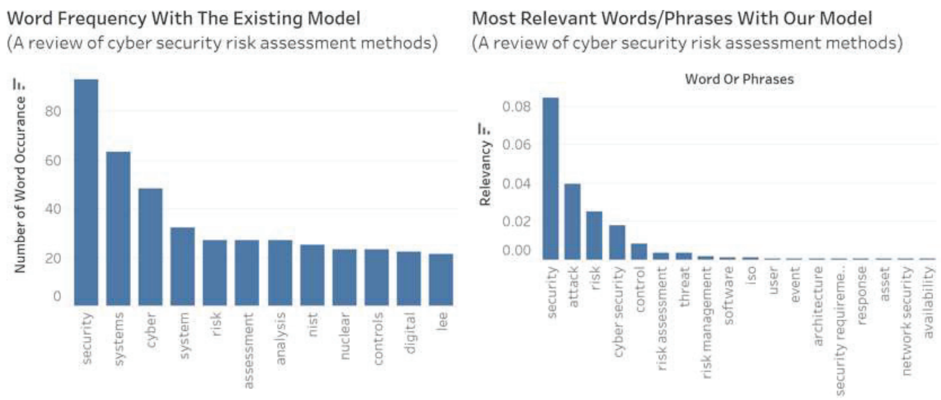

Figure 1. Comparing The Topical And Thematic Analysis Of Two Papers Using Both the Existing and Our New Model

Keywords: *Topical and thematic analysis, decision support, term frequency, relevancy, domain lexicon*

Integration of Bayesian network and multi-objective evolutionary algorithms for evaluating land combat vehicle system

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Abstract: The interactions between land combat vehicle (LCV) components defined by logical or physical links together with the different types of operational scenarios and threats provide a challenge to decision makers (DMs) in providing a clear answer to the problem of determining the 'best' combination of LCV system configurations. This study integrates Bayesian network (BN) and multi-objective evolutionary algorithms (MOEA) to present an interactive analysis tool for evaluating and optimising the operational impact of different LCV system specifications and configurations. BN is employed to establish a qualitative and quantitative representation of the relations between the variables of the LCV system considered and to calculate standard values of uncertain LCV capabilities like survivability, lethality, and etc. MOEA are adopted to remove the difficulty of the elicitation process for quantifying DMs' preferences in the highest levels of multi-criteria decision making (MCDM), to manage the combinatorial nature of the number of LCV system options available and to help the DMs to avoid any arbitrary selection of sub-optimum baseline vehicles. Searching for the 'best' option will no longer need all possible system configurations evaluated when deploying MOEA and can be obtained in few minutes compared to a few hours with the brute-force search (complete enumeration) approach in our previous work[1].

Unclassified

Option Design (Once Design selected, click 'Searching Best Options' Button to see results) →→→

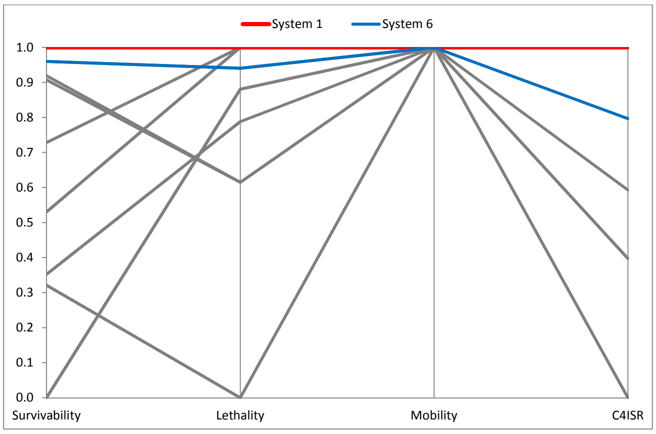
System Configuration	Fixed or Free
Config 1	Opt 1
Config 2	Free
Config 3	Free
Config 4	Free
Config 5	Free
Config 6	Free
Config 7	Free
Config 8	Free
Config 9	Free
Config 10	Free
Config 11	Free
Config 12	Free
Config 13	Free
Config 14	Free
Config 15	Opt 1
Terrain	Open

Unclassified

Searching 'Best' Options

Maximising Capability (Yes/No)	
Survivability	Yes
Lethality	Yes
Mobility	Yes
C4ISR	Yes

	System 1	System 2	System 3	System 4	System 5	System 6	System 7	System 8	System 9
Survivability	49.00%	48.76%	48.59%	48.93%	48.92%	48.96%	48.13%	48.41%	48.43%
Lethality	76.80%	76.80%	76.80%	75.50%	75.50%	76.60%	76.40%	73.44%	76.09%
Mobility	83.33%	83.33%	83.33%	83.33%	83.33%	83.33%	83.33%	83.33%	83.33%
C4ISR	86.45%	86.45%	86.45%	86.45%	86.45%	84.14%	81.84%	79.63%	75.13%



In order to fully incorporate the selection flexibility of the system/scenario configurations into the optimisation procedure, a graphical user interface was created that defined the population members (restricted LCV systems by pre-selecting some of its configurations, if wanted) currently being evaluated and also allows changes to the number of objectives to be optimised. The interactive analysis tool is a Microsoft Excel workbook 'packaged' with public software allowing the required calculations to be completely automated and results to be captured in both tabular and graphical forms.

The proposed methodology provides modelling and data collection structures that assist in making explicit the LCV configurations, scenario parameters, and DMs' preferences, as well as providing a tool for automating/documenting some of the time-consuming evaluation processes.

[1]Nguyen, M.-T. and T. Cao (2017). A hybrid decision making model for evaluating land combat vehicle system. In G. Syme, D. Hatton MacDonald, B. Fulton, and J. Piantadosi (Eds.), *22nd International Congress on Modelling and Simulation, MODSIM2017*, Hobart, Australia, pp. 1399–1405.

Keywords: *Bayesian network, multi-criteria decision making, MCDM, Pareto optimisation, multi-objective evolutionary algorithms*

Fishing for the Unknown Unknowns: A Bayesian Perspective

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Abstract: In this study, we consider the mathematical framework for *inductive* or *plausible reasoning*, or in other words, mathematically rigorous reasoning with uncertainty [1-3], which extends the well-known framework for *logical* or *deductive reasoning* (often simply called *logic*), based on certainty. This framework makes use of the Bayesian interpretation of probabilities as *plausibilities*, or mathematical parameters assigned a value from 0 to 1, based on what is known. Importantly, these need not correspond to measurable frequencies, for example from the collection of an infinite number of samples from a fixed population. Probabilities identified as plausibilities have been shown to satisfy the same mathematical rules as probabilities defined as measurable frequencies, based on the product and sum rules of probability theory [1-3]. However, they are of much broader application. In particular, Bayes' rule [4-5] enables a user to calculate the "probability of an hypothesis, given the data", or in other words the degree of belief or disbelief in the hypothesis, given what is known. Since its mathematical foundation is formulated to be universal in application, without exception, this provides a common platform for hypothesis testing, model comparison, parameter estimation or any other form of inference, and can be used in subsequent decision frameworks such as utility / loss analysis or risk assessment. In consequence, no construct other than that of probability is necessary for the analysis of uncertainty.

We then examine the "Rumsfeld trifecta" of *known knowns, known unknowns* and *unknown unknowns* from the Bayesian perspective. By symmetry, it is shown that all such influences must be handled identically mathematically, regardless of whether they are known or unknown, or even if their existence is known. In consequence, if any unknown unknowns have an influence on the hypothesis or model space of a given problem, their influence can be calculated mathematically from their corresponding influence on the data. Using this insight, we derive a form of Bayes' rule which directly gives the probability of the unknown unknowns, based on the data. This enables a user to identify the existence of unknown unknowns directly from the data.

We then examine an extended set of influences composed of the Rumsfield trifecta and also the *unknown knowns*, i.e., those influences which are known but are accidentally or deliberately ignored. For many prob-lems, including military problems, these can arguably be of greater importance than the unknown unknowns. We show that the above mathematical insights also apply within this enlarged four-fold classification.

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Keywords: *Bayesian inference, uncertainty, identification of unknown unknowns*

Data farming and data analysis for tackling uncertainty in major Defence workforce transitions

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Abstract: With the introduction of new Defence platforms comes the requirement for large-scale workforce transitions and retraining. This is especially difficult during the initial planning stages, where a large number of parameters such as training requirements, workforce availability, attrition and resource availability, are uncertain. To further complicate matters, the workforce structure in Defence is extremely complex with many interdependencies and feedback loops pertaining to requirements on the level of experience and proficiency for different groups of personnel. As such, creating effective and robust workforce transition plans requires Defence to plan for and understand many different future outcomes and the different effects of each on the workforce.

To assist decision making under uncertainty, a lightweight Markov Chain Monte Carlo (MCMC) simulator was created to model the flow of personnel through part of the Australian Defence Force continuum which is a complex network of courses and postings. Probability matrices were used to describe attrition rates, training failure rates, platform maintenance periods and changing personnel numbers. The simulator was able to test different scenarios of the controllable, yet uncertain, parameters of the workforce, such as training additional instructors or diverting personnel from other units. Monte Carlo analysis was then used to sample parameters from those that are uncertain and uncontrollable, such as the attrition rate and the platform delivery date. However, the workforce planning for transitions may begin well before many of these parameters are certain, leading to an extremely large number of combinations of different levels of parameters.

To address this problem, data farming was used with the simulator and through design of experiments the number of simulations required to effectively explore a broad range of the input parameter space was reduced. In this way, values for the parameters were sampled from their input ranges and then executed within the simulator. Nearly Orthogonal Latin Hypercube (NOLH) sampling was used to sample data from these input ranges, which ensured that the sets of the input parameters tested, known as design points, filled the input parameter space effectively and prevented the occurrence of unintended correlations between the design points. A total of 512 design points were created from 28 parameters, each with varying ranges.

The output number of personnel in different positions at critical times – response variables – were then compared and analysed for these 512 design points. The dependency between the different parameters was determined by calculating Spearman's rank correlation coefficient for each parameter against these response variables as correlated across the different design points. Heat maps were produced which depicted the strength of this correlation and could inform workforce planners on which parameters would likely have the greatest influence on personnel numbers during the workforce transition. Regression analysis was also performed in the form of regression trees, which involved iteratively partitioning the output data at points which would minimise the overall sum of squares error. This then formed a regression tree which could not only identify critical decision points during the transition, but also provide workforce planners with the most appropriate course of action depending on the outcome of the uncertain parameters.

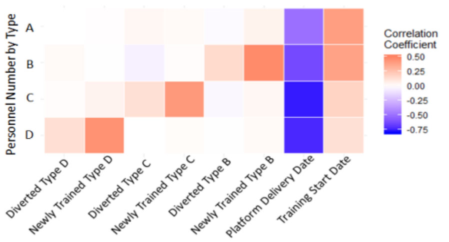

Figure 1. Spearman correlation heat map for a subset of workforce transition parameters

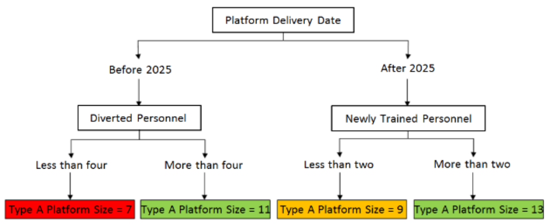

Figure 2. Regression tree for a subset of workforce transition parameters

Keywords: *Workforce planning, data farming, workforce transitions, uncertainty planning*

Multi-stock replenishment of naval vessels by specialist replenishment ships

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Abstract: Naval replenishment vessels play an important role in military operations as they resupply and sustain other military units, allowing them to react quickly and perform their required roles for an extended period of time. They may replenish naval task groups with fuel (both maritime fuel and aviation fuel for helicopters), stocks (food, ammunition etc.), and also may support deployed land forces.

This study examines the trade-offs between various replenishment ship types supporting naval operations, and finds through sensitivity analysis that the level of risk regarding fuel and stock availability a task group of ships wishes to take on is a key factor in determining an optimal replenishment fleet. A scheduling model was built in which a task group of military assets was replenished indefinitely by replenishment vessels, which travelled back and forth to a distant port to restock themselves. Subject to constraints and demands, a number of measures of effectiveness were developed in order to examine the replenishment ship fleet. These include the amount of time a replenishment ship is not needed and remains in port (slack time) within a particular schedule, and the maximum distance off shore a combination of replenishment ships can support naval and joint operations.

Keywords: *Operations Analysis, scheduling, replenishment, optimisation*

Ranking Defence Systems using SCMILE data

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Abstract: The SCMILE Services Framework is a service based approach to model interdependencies between Defence systems in terms of services provided and consumed (Lowe et al 2006). These services are categorized as Sensing (S), Command and Control (C), Physical Mobility (M), Information Mobility (I), Logistics and Support (L), and Engagement (E), or simply SCMILE. A four-point numerical scale is used to measure the strength of the interdependencies between systems based on Subject Mater Experts' assessment of the criticality of services to mission success. A Defence investment program usually involves hundreds or thousands of systems and thus a large amount of SCMILE data will be generated. One of the challenging questions is how to measure, identify, and rank the systems from the generated SCMILE data.

This paper explores methods to analyse the ranking of systems from SCMILE data based on network analysis algorithms that are directly applied or can be adapted. The Defence systems are viewed as the nodes and the SCMILE service links as edges in a directed weighted graph, where the weights represent the criticality values of the links. The SCMILE interdependency data is then formulated as a weighted adjacency matrix. We consider a broad class of parameterized node importance measures for network analysis. These measures are expressed in terms of functions of adjacency matrices and generalise various well-known importance indices, including degree measures, Katz index, Decision Making Trial and Evaluation Laboratory (DEMATEL), and eigenvector measures. We also consider web searching algorithms such as the Hypertext Induced Topic Search (HITS), and PageRank. We present a 2-d map of ranking results to cluster systems according to the ranking scores.

Experimental results from analyzing Defence SCMILE data show that: (1) by tuning the discounting parameter α of the Katz index, the ranking results are highly correlated between the degree ranking (a purely local measure), DEMATEL, and the eigenvector ranking (a global measure); when α tends to 1, the Katz index ranking tends to be consistent with the eigenvector ranking, but when α is close to zero the Katz index does not tend to be consistent with the degree ranking (a result expected for undirected graphs); (2) a modified PageRank algorithm we call SyS_Rank is a global ranking algorithm and is robust in terms of the sensitivities to the perturbation of edge weight values; it also has the advantages of dealing with the dangle nodes; and (3) HITS algorithm produces two importance scores for each node simultaneously, one for the provider, another for the consumer. The mutual reinforcement in HITS indicates that a "good" provider must provide to several "good" consumers and vice versa. For SCMILE data, HITS also provides the scores to measure the similarity between the co-providers/consumers.

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***Keywords*:** *Directed graph, network analysis, node ranking*

Aggregation of dependent criteria in multicriteria decision making problems by means of capacities

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Abstract: We address the multiple criteria decision problem in which the criteria are mutually dependent, in the context of land combat vehicle selection for Australian Defense. We employ the theory of capacities to model criteria dependencies. Its challenge is exponentially growing (with the number of criteria) set of parameters that represent all criteria interactions. We outline a number of strategies to (a) simplify the construction process and reduce the number of parameters, and (b) elicit preferences from the decision makers and translate them into capacity learning problem. We present various challenges and ways to address them from the mathematical programming perspective.

Keywords: *Capacity, Fuzzy measure, MCDM, Choquet integral, dependent criteria*

Multi-Criteria Prioritisation of Defence Projects Based on Best-Worst Method

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Abstract: Multi-Criteria Decision Analysis (MCDA) methods typically involve Subject Matter Experts (SMEs) working through numerous questions comparing one of n decision alternatives to another, for each of one or more decision criteria. Recently the Best-Worst Method has gained in popularity because it significantly reduces the number of pairwise comparisons that are required by other MCDA methods such as Analytical Hierarchy Process (AHP), from $O(n^2)$ to $O(n)$. Nevertheless, pairwise comparison is problematic when the decision alternatives fall into different classes and do not lend themselves to direct comparison, or if the decision criteria aren't equally relevant to all classes.

The authors have developed a prototype multi-criteria decision support method and accompanying tool called Operations Research Defence Elicitation and Ranking System (ORDERS). An overview of the design and implementation is given. Key features of ORDERS include the disaggregation of capabilities into SME specific topic domains, streamlined within-domain pairwise comparison and elicitation using a Best-Worst approach, collaborative negotiation of overall relative orderings, sublist rescaling and sensitivity analysis.

ORDERS has been successfully used in an SME-backed workshop to prioritise a client's capability investments for subsequent input into Force Structure Plan 2019 cross-service negotiations. An appraisal of the outcomes of the workshop and efficacy of the ORDERS method is given.

Keywords: *Multi-Criteria Decision Analysis, Best-Worst Method, Analytical Hierarchy Process, Expert Elicitation*

A Novel Approach to informing the Future Land Force: Incorporating Design Thinking and Concept, Development and Exploration Methods

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Abstract: The future is complex and uncertain, with emerging technologies that present significant potential advantages as well as threats. In the face of such rapid change, the land force must be able to continue to operate now and be able to adapt and innovate to achieve success in the future. So how can the ADF evolve and both incorporate incremental improvements and embrace radical step change and divestment in order to invest in new concepts that exploit emerging technology?

This paper describes DST Group and Army Headquarters' collaboration to design an aspirational Battle Group (BG) that could achieve success within the 2035 Australian Primary Operating Environment (2035 POE). Key aspects of the 2035 POE are pervasive unmanned aerial systems and sensors more generally, increased lethality and availability of precision munitions, increased capabilities to counter fires, increased availability of electronic warfare effects, and advances in networking leading to highly collaborative effects. Additionally it was assumed that autonomy and AI advances would enable reduction in cognitive burden alleviating the need for tele-operation or remote control, enabling greater numbers of Robotic and Autonomous Systems (RAS) resident within the 2035 BG without reducing the number of combat personnel. Significantly, potential adversary use of these same capabilities would not be constrained by the same legal and ethical constraints as the ADF.

For DST Group, this represents a change in focus to designing concepts and developing force options in addition to assessing them to inform capability decisions. As a result we developed the Design, Concept Development and Exploration (DCDE) approach which took aspects of the NATO Concept Development and Experimentation process, US Army Campaign of Learning approach and UK Disruptive Technology Assessment Games and combined them with Design Thinking methods. A key difference of the DCDE approach is the use of wargaming as an immersive method for concept exploration to exploit emerging technology. The DCDE approach included four key phases; align, design, analyse and refine, which were iterated with the refine phase running concurrently through the entire campaign. This is similar to the Design Thinking philosophy of understand, define, ideate, prototype and test. Flexibility and agility was built into the DCDE approach through the use of multiple methods for analysis with each activity designed to incorporate and respond to findings of preceding activities.

The prototype 2035 BG designed using the DCDE approach, balanced novel concepts with current constraints of legacy systems and structures. The 2035 BG gained significant advantage beyond the current 2028 Integrated Investment Program realised (funded) force through use of numerous RAS enabled systems to provide enhanced ISR, EW and fires down to the lowest possible level. 2035 BG concepts included: use of enhanced networking and agile C2 to achieve both survivability and lethality effects at the lowest levels, use of integrated Counter Rocket Artillery and Missile Systems and Counter Unmanned Air Systems; offensive and defensive EW including deception and decoy tactics. The emerging technology areas and corresponding concepts identified for further investigation are consistent with findings from other studies but have also been contextualised for the 2035 POE.

The DCDE approach represents a novel approach to design a force combining iterative Design Thinking methods and wargaming to provide immersion in context for exploration before detailed testing and assessment. Key benefits of the DCDE approach are flexibility, efficiency, responsiveness and a closer alignment with decision maker needs. The DCDE approach applies a range of methods, models and tools to build an evidence base for modernisation and investment decisions.

Keywords: *Force design, Concept development, Wargaming, Red teaming, Military experimentation*

Exploiting ecological non-trophic models in representations of warfare

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Abstract: Traditional combat models such as the Lanchester model are typically limited to two competing populations and exhibit either exponential growth or decay solutions. Although these early models were well suited to the type of warfare in the early twentieth century, they are no longer as directly applicable to the complex modern military operating environment. Despite these shortcomings, the Lanchester model was used in the Operations Research of Force Design even in World War II, as evidenced in the classic work *Methods of Operations Research* of Morse and Kimball [1950]. Our work seeks to enrich such models to account for modern and future complexities, particularly around the role of inter-agency engagement in operations.

To this end, we account for the presence of civilian or non-combatant populations, which have long been an unfortunate part of the combat setting as they are directly impacted by the warfare surrounding them. Typically this non-combatant group consists of the host population in the space where combat occurs. The other type of non-combatant groups, a development since the 19th century and with ongoing evolution today, are agencies, be they governmental or non-governmental, that undertake work in conflict environments to support local populations. Depending on whether they are governmental or otherwise, these agencies have a range of formal and informal relationships with both sides of the conflict. As the agency non-combatant populations play no direct role in combat, their interactions with the two combatant forces are well suited to be modelled through the recent developments in non-trophic ecological models.

The networked non-trophic ecological model is one of the most recent developments in ecological modelling that incorporates a great number of positive and negative interactions, both trophic (consumptive) and non-trophic (non-consumptive), between multiple species in a "multiplex" network. In a similar manner in which the Lanchester combat model can be viewed as an adaptation of the Lotka-Volterra model for two species in a predator-prey relationship, the networked non-trophic ecological model can be exploited as a viable representation of modern combat in which non-combatant groups exist.

The combat model presented in this paper provides a global representation of asymmetrical combat between two forces in the modern setting where non-combatant populations are present. In our model, the non-combatant population is present as a neutral agency supporting the native population to the extent that they are non-combatants, but where there can be leakage from this group to the insurgent fighting force. Correspondingly, the opposing intervention force is under obligations to enable an environment where the neutral agency may undertake its work. A key result of our model is that, in contrast to the typical exponential growth or decay solutions of the Lanchester system, with the inclusion of a third group limit cycles and bifurcations can now occur which we interpret in light of the warfighting application of the model.

Keywords: *Combat models, non-trophic interactions, Lanchester's laws, future force, operating environment*

Baselining the Whole-of-Force Capability and Capacity of the Australian Defence Force

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Abstract: This paper outlines an analytical approach taken to baseline the whole-of-force capability and capacity of the objective Australian Defence Force (ADF) (i.e. the projected force). This was achieved by capturing structured subjective assessments from subject matter experts (SMEs) drawn from across Defence. Approximately 200 SMEs participated in the assessments and were split into syndicates of 20 – 30 participants. Each syndicate completed a series of tasks to identify their subjective assessment of the ADF in eight Australian Capability Context Scenario's (ACCS). This was performed for both an individual ACCS and concurrent ACCS over four time epochs. The following tasks were performed by each syndicate for an individual ACCS: (i) Develop a Concept of Operations (CONOPS) specific to the ACCS; (ii) build a force model, comprising types and quantities of Defence Elements (e.g. platform such as F-35A Joint Strike Fighter or Infantry Fighting Battalion), that was constrained by the objective Australian Defence Force inventory; and (iii) perform a structured subjective assessment to determine the performance of the force model to realise the CONOPS. For concurrency, where a syndicate was assigned multiple (two to four) ACCS', the outputs from the individual ACCS were provided and their task was to rationalise the multiple force models to be constrained by a singular ADF inventory. Each syndicate performed a reassessment of the revised force models to realise each individual concept of operation. The outcome of these tasks enabled the identification of high and low performance of the ADF in a specific context (i.e. capability and capacity of Defence Elements specific to a scenario). This paper holds that a judgement-based form of decision support modelling (a form of multi-criteria decision making) provided appropriate structured analytical support to some of the most critical decisions to be made by the Department of Defence within the time-constraints imposed.

Keywords: *Force structure plans, Defence capability assessment, Objective Force, Military force performance*

Narrative visualisation of simulations: Finding the stories within the data

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Abstract: Decision makers need to understand and draw key insights from large and complex data sets generated by simulations. This may be to answer a specified analytical problem addressed by a simulation or to support learning or mission objectives through after-action review of a virtual simulation. Geospatial displays are traditionally used to help a decision maker or analyst gain an understanding of the results of a force-on-force constructive simulation, or for after-action review of virtual simulations. They provide an evolving picture of the geospatial positions and spatial relationships between entities and key features in the environment, and can potentially incorporate other attributes such as entity state or key metrics to support the analyst. However, while this geospatial context is often important, sense-making also requires an understanding of the significant actors, their relationships, their interactions, and the consequences of these relationships and consequences. Narrative visualisation is an approach that focusses on the storylines of key actors, the events they are involved in, and the causal relationships between entities – i.e. the stories within the data. This paper describes initial work demonstrating a novel narrative visualisation approach for data from a large-scale force-on-force simulation, and the key features of this visualisation that supports a decision maker or analyst's understanding and insights on what occurred within the simulation, and why. To the authors' knowledge, this represents the first time simulation data has been applied to narrative visualisation. While still in its early stages, this approach shows promise and could potentially supplement, or indeed replace, geospatial-centric visualisations as the primary sense-making pathway for analysts in a wide range of operating domains, including real-time operating pictures. This is particularly apropos in domains where the geospatial context is less relevant.

Keywords: *Narrative visualisation, storytelling, analysis, after-action-review, sense-making*

Applying reinforcement learning techniques to operations-level wargaming scenarios

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Abstract: Wargaming has long been a tool used by military analysts and decision-makers to improve, optimise, and better understand whole-of-force operations. In modern times, this process has been digitised, with wargaming scenarios being played-out using agent-based simulations, resulting in complex multi-dimensional datasets for analysis. One such simulation is the Joint Future Operating Concept Explorer (JFOrCE) which incorporates artificial intelligence (AI) behaviours for common military entities such as fighter jets, ground based air defence, submarines, light and heavy vehicles, and airborne early warning and control systems.

This work argues that a key to obtaining sensible data from these simulations is the realism of the AI behaviours within them and sensible decisions to be made by the AI, else the final results of the simulation may be unreliable in nature. Alongside work in providing improved visualisation of the complex outputs of wargaming simulations, previous work has applied genetic algorithms and decision trees at operations- and entity-level wargaming.

This work consists of two core components: (a) a proposed approach for implementing Reinforcement Learning (specifically Deep Q-Learning) for wargaming scenarios and (b) a novel utility for implementing Reinforcement Learning with the common agent-based modelling software NetLogo[1].

Reinforcement Learning in Wargaming: The AI behaviours previously implemented in JFOrCE use simple if-then rules for determining if an action should take place (e.g. deploy a jet to attack a target, return a jet from a mission, positioning sensor entities, etc.) Written in NetLogo code, these rules are limited in the intelligence, realism, and uncertainties (when played in an interactive scenario) they can offer. A suitable alternative to these rules may be found in Q-Learning, whereby an agent "learns" a policy—i.e. what actions (if any) to take in response to a given observed state that will result in a probable positive outcome for the agent. Famously applied to Atari 2600 games with DeepMind, Deep Q-Learning could be used in the space of wargaming where the problem space is much the same—given a specific state of the observable battlefield, what are the optimal actions that can be taken to put the agent in a state more likely to result in victory? Challenges in this space include determining concise and relevant observations for agents.

In addition to resulting in potentially more accurate simulation results, the resulting trained agents could be used in practice in interactive wargaming scenarios in two ways. The first is a formidable opponent with the capability of adapting to player behaviour, potentially resulting in a more effective training and education tool. The second is an assistant AI to help guide players in what actions they could take. The latter of these approaches presents an interesting environment in which to implement Explainable AI, which is beyond the scope of this paper.

A Reinforcement Learning Tool for NetLogo: A practical challenge in implementing reinforcement learning in JFOrCE is the underlying software architecture, which is NetLogo. This work presents a novel approach to integrating a NetLogo environment with the commonly used reinforcement learning toolchain such as TensorFlow (https://www.tensorflow.org/). A wrapper Python environment was developed which sends commands to and receives reports from NetLogo. The developed tool can be used with any NetLogo model, with very minor setup required. Given the widespread use of NetLogo due to its simple scripting language, this tool may improve researchers' abilities to prototype reinforcement learning environments without the need to use complex engines.

Conclusion: This work and the corresponding presentation will demonstrate the Reinforcement Learning tool developed within the context of the wargaming simulation JFOrCE, and how it can be applied to effectively any NetLogo model. A discussion of the challenges in applying Deep Q-Learning to JFOrCE will also be presented.

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Keywords: *Simulation and modelling, Artificial Intelligence, Reinforcement Learning, NetLogo, wargaming*

Identifying intelligence links in threat networks through machine learning on explosives chemical data

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Abstract: Improvised Explosive Devices (IEDs) and the terrorist or threat networks that employ them pose an ongoing threat in military operations. A significant challenge is identifying the intelligence linkages and relationships between the individuals that form these threat networks. However, this information is essential if these networks are to be disrupted.

This paper presents a novel concept for identifying these network linkages that can complement the threat network understanding generated through traditional military intelligence means.

In searching for opportunities to develop additional intelligence through scientific research, it was identified that the improvised nature of IEDs introduces characteristics that may be unique to each bombmaker. Improvised devices are made by individuals (not a production factory) so their construction, components and characteristics vary based on the maker. Based on the assumption that a bombmaker will regularly make IEDs in the same way (often the way they have been trained to make them), there is the opportunity to identify matching IEDs that have been made by the same maker, creating links between a person and multiple IEDs or attacks. Similarly, there may be common construction characteristics between different bombmakers IEDs enabling linking bombmakers together through their training, construction techniques or materials.

To exploit this opportunity, this research utilises the application of data science and machine learning techniques to analyse chemical test data from recovered samples of explosives, with the aim of identifying matches and relationships between the samples. Previously, forensic chemists have demonstrated the ability to identify matches between explosive samples through detailed chemical analysis. However, this analysis was a manual and time-consuming process using advanced chemical testing techniques and could not be applied at a large scale. The use of data science aims to reduce the need for advanced testing and enable rapid analysis of large data sets.

The methodology presented combines machine learning clustering techniques with traditional chemometric techniques for analysing chemical test data. The process can be summarised as follows:

1. Data pre-processing is used to optimise the data for clustering analysis
2. Principal Component Analysis (PCA) is used to reduce the dimensionality of the data and provides a way of visualising the clustering in 2-dimensions
3. Unsupervised machine learning algorithms then assign the explosive samples into clusters
4. Evaluation (validation) of clustering results and confirmation of the number of clusters is achieved through application of internal and external evaluation indices.

The results presented demonstrate the feasibility of using this machine learning centred approach for matching samples of unknown explosives that could be made by the same bombmaker.

Keywords: *Clustering, unsupervised machine learning, explosives, spectroscopy, intelligence*

An embodied cognition classifier of human emotion and senses

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Abstract: Drawing on the idea of embodied cognition, where the human body and its environment influence the way a person thinks and feels, we test if it is possible to classify suicide attackers from their writing by using words affected by the emotional and modality-specific systems in the brain. We use their final notes and manifestos compared with normal bloggers' posts to train a machine learning classifier. We compare two support vector machine classifier models using linear and radial base function kernels. In this exploratory study, receiver operating characteristic curves show encouraging separation accuracies. These models offer an 11-13% improvement over methods using only emotion or sense categories. This study supports the idea that an embodied cognition classifier better discriminates the way a person thinks and feels rather than treating the body and mind as separate entities and may help in reflecting behavior and applying influence in online social systems.

Keywords: *Machine learning, vector support machines, suicide terrorism, embodied cognition*

Evolving behaviour trees for automated discovery of novel combat strategy in real-time strategy wargames

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Abstract: A wargame is defined as: "A simulation, by whatever means, of a military operation involving two or more opposing forces using rules, data, and procedures designed to depict an actual or assumed real life situation" (Gortney 2016, p503). Wargaming is used for several purposes, such as teaching strategic planning, practising the tasks associated with war, and analytic purposes (Burns et al., 2015). While wargaming is predominantly a human centric analytical activity, it is an area where artificial intelligence (AI) may play a useful role because of a computer's ability to play through a wider range of possible strategies. However, creating simulated AI participants for wargame scenarios is challenging because of the complexity and uncertainty in the environments in which they exist. The recent rise of automated behaviour discovery for agents in a variety of games traditionally dominated by humans offers a possible solution. Commercial real-time strategy (RTS) games provide an abstract simulation of a world where players aim to dominate and defeat other players by acquiring, using and managing resources, often including a mix of military, political, scientific and economic factors. As there is considerable overlap between the objectives found in RTS games to those that exist in military style wargames, RTS games are ideal platforms to conduct research and development in support of our AI-enabled wargaming research objectives.

In this paper, we document our work on the use of evolutionary algorithms for automated behaviour discovery, where evolved behaviour trees are used as controllers for the blue team entities in the wargaming simulation. As behaviour trees are constructs formulated as a tree-type graph data structure, genetic programming (Koza, 1992), a technique developed specifically for the evolution of such structures was employed. In order to systematically evaluate the approach in terms of novel behaviour discovery, two test scenarios were designed to isolate particular features of land-based combat, inspired by terrain design patterns from computer games. A more complex scenario, involving multiple terrain constructs was also evaluated.

A set of experiments were run on the developed scenarios to evolve a blue team against a static red team opponent. The red entities employed a reactive AI, with the simplicity of the red AI balanced by having a much greater number of red units in the scenario. Results from the experiments indicate that evolved behaviour tree controllers in a multi-agent scenario can be useful to identify a set of behaviours that exploit the properties of the scenario and lead to victory. In particular, we observed the 'expected' behaviour in the control scenarios:

- Units learned to work together as a team, for example, armor units shielding artillery units.
- Units in a relatively weak blue side learned to exploit a chokepoint in the terrain to defeat a superior red side.
- Units learned to avoid dangerous sections of terrain, such as those protected by enemy snipers.

Keywords: *Wargames, evolution of behaviour trees, genetic programming*

Towards an intelligent agent for a Humanitarian Aid Disaster Relief wargame

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Abstract: Analytical wargames are part of a suite of tools that the Land Capability Analysis (LCA) branch of the Defence Science and Technology (DST) Group utilises in order to help decision makers understand the issues and challenges in real world events. A wargame typically consists of a set of rules, procedures and adjudications that allow players to simulate their decision choices over a predefined scenario enabling them to gain knowledge and experience towards a potential real world situation. While wargames are usually played out by human participants, recent advances in game-playing artificial intelligence (AI) have prompted questions about the roles that intelligent agents may play within the analytical wargaming space. Assuming the rules of the game is largely well defined and static, the main advantage of such agents is their ability to play through and explore large sections of the wargaming space in a short amount of time, generating vast amounts of data that allows human participants to gain insight about the problem space. Intelligent agents may also play a role as an active adversary in the absence of a human one, continually challenging a player's intended actions and or assumptions enabling the participant to explore the ramifications of their decision making processes. Furthermore, such agents will have the capacity to generate novel strategies for playing wargames. The potential of such future capabilities are being investigated within the AI-enabled Wargaming theme of DST's Modelling Complex Warfighting Strategic Research Investment.

This work describes the progress that has been made so far in building intelligent agents for an in-house wargame titled "Disaster at the Joadia Islands" (JOADIA) created by Peter Williams. JOADIA is a turn-based board game featuring an abstracted Humanitarian Aid Disaster Relief scenario over a fictitious set of contested islands. Players have control over a set of defence elements (land, air and maritime) that are each capable of performing different joint warfighting functions (e.g., ISR, airlift, stabilisation operations) with the goal of evacuating as many civilians as possible that have been affected by a tsunami within a limited number of turns. The use of intelligent agents in the wargaming domain requires a computerised model of a wargame with formalised rules. A digital model of the rule set was constructed and now serves as the platform for conducting our intelligent agent research. While JOADIA features players for both blue and red sides, we begin by constructing an intelligent agent that is capable of playing the blue side. By considering the blue side problem perspective only (and without an adversary red player), the JOADIA problem space may be conceptualised as an optimisation of a multi resource allocation problem. JOADIA is a complex game to play for both humans and AI - it is non-deterministic, partially-observable and has a calculated game-tree complexity of approximately 10^{196}. We use Monte Carlo beam search to effectively search through the vast action space and find promising sequences of actions that maximise civilian rescues, while minimising civilian deaths. Finally, by considering the force mix combination as one of the agent's actions, this search method also allows us to find effective force mixes.

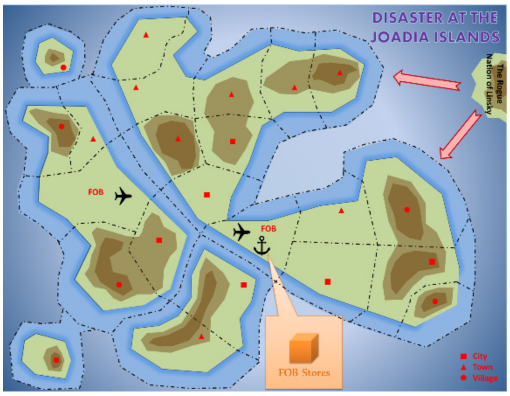

Figure 1. JOADIA game map

The model of JOADIA introduced in this paper provides a rich environment to further explore AI and decision support research in a relatively accessible wargame setting. This will enable us to experiment on different approaches towards addressing the question behind the role to be played by intelligent agents in analytical wargames. Our future work aims to incorporate actions of the red player, reduce the search space by utilising higher-level actions and investigate alternative AI methods for agent learning strategies in JOADIA.

Keywords: *Wargaming, intelligent agents, search, modelling*

Correspondence analysis approach to examine the Nobel Prize

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Abstract: The main goal of this study is to examine Nobel Prize data by exploring and studying the association between the Country of the nominated individual (or of the nominated team) and the Discipline in which the Nobel Prize was awarded. The sample studied comprises the eight the most developed countries that received at least one Nobel Prize in the period from 1901 to 2018; these being Canada, France, Germany, Italy, Japan, Russia, British Isles and the USA. The variables Country and Discipline are cross-classified to form a two-way contingency table. Simple correspondence analysis is performed to explore the nature of the association between these two variables.

Keywords: *Simple correspondence analysis, Chi squared test of independence, Nobel Prize*

EXTENDED ABSTRACT ONLY

Towards a digital twin: getting to know your data

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Abstract: In the Manufacturing sector, the fourth Industrial Revolution – or Industry 4.0 – new technologies and models are changing all aspects of operations. One part of this is an interest in building so-called 'digital twins' and 'digital system models'. These concepts refer to exact replicas of individual physical objects and the processes which create those objects, including the ability to access state information in real time and to simulate the evolution of that state. This leans on a problem well-known in Operations Research: the challenge of getting quality data, well understood and in good time.

Here, we discuss approaches derived from interactions with three companies, demonstrating initial steps in getting to know your data – statistical, process and systems approaches. A statistical approach includes understanding the kind of distribution product features have, analogous to quality control limits. A process approach could consider sequencing, and the effect on a time series view of a quality impact at some point in the sequence. Systems approaches consider multi-criteria decision-making, including human factors. For many operations, it is necessary to learn that the data required for useful modelling is different to that for managing day to day operations.

With the first company, the purpose in building a digital systems model was to be able to reduce the time taken to establish the source of quality control failures from a set of machines and processes. They had taken steps to ensure that each individual part manufactured in their high volume, medium value production process was individually marked with a physical identifier due to provenance requirements from their customer, but these identifiers were not correlated to the process sequence nor logged at every step. In this case, process control charts were used to understand aggregation and drift of various characteristics such as die temperature, and big-screen dashboards were used to build a culture of using data to manage interventions to identify quality concerns.

In the second case, the underlying issue was to understand the machine cost / time for making different parts. The usual approaches such as Sankey diagrams had been created to identify the order flow in principle; but in this case, use of on-part and sub-assembly identification technologies was not simple due to processes such as powder-coating, which obscures barcodes and damages low-cost RFIDs. With a wide variety of parts, the key activities were to visualise distributions in the timing data for different models to understand what can and cannot be safely characterized by a normal distribution, and the use of clustering techniques to understand which of the many characteristics of the various parts produced should inform a baseline digital system model of the manufacturing process.

Finally, with a manufacturer of low-volume, high value products, we have created multiple digital models of their operations to support situational awareness, forecasting and on-line optimization for recovery from delays. We draw two major conclusions from this. Firstly, there can be no all-encompassing digital twin, as different models need to use different assumptions. Secondly, data is collected for a reason, and that it can, from a modelling perspective, be wrong while still being fit for purpose for its design criteria. This demonstrates a critical issue in using found data for building digital twins.

This work demonstrates that there is a significant gap between the current perception of digital twins and digital systems models and their utility and capability, and the reality of the cost and complexity of actually building such models. Significant effort is required in understanding both the data needed to fully describe a process, and the approaches to collect this data effectively, recognizing that this may be very different to currently available operational data.

Keywords: *Industry 4.0, digital twin*

Machine-based Production Scheduling for Rotomoulded Plastics Manufacturing

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Abstract: Rotational moulding (Rotomoulding) is a production process commonly used to create a range of hollow plastics including storage tanks, leisure craft and medical products. While rotomoulded products are diverse, all follow the same general production process. Material is placed into a hollow mould which is attached to the arm of a rotomoulding machine. Rotomoulding machines contain an oven, capable of housing one arm and its attached moulds. When heated, the powder melts and the arm rotates the attached moulds on all axes to evenly distribute material around the walls of the moulds. The arm is taken out of the oven once moulds are sufficiently cooked, and the arm continues to rotate whilst moulds are cooled to ensure material sets evenly before moulds are removed from the machine and products are finished. As multiple fixing points generally exist on an arm, products may be batched together and processed simultaneously. Batching is however restricted by the area available on the machine arm, and the compatibility of cook/cool times of products. Rotomoulding machines are also very diverse, restricting their ability to process certain products. These considerations all have implications for scheduling in this environment, making it an interesting and challenging problem.

The problem is formulated as a mixed integer program (MIP), with the objective of minimising total tardiness. The problem has some commonality with hybrid flow shop scheduling with batching, where additional constraints are needed to control which machines may be used at each stage. To simplify the model, batches are pre-assigned to machines and positions in the schedule, thereby absorbing machine assignment and sequencing decisions into the batch allocation decision. The performance of the MIP was tested using a range of randomly generated problem instances. The problem instances were based on historical data provided by industry partners Global Rotomoulding and are generated to be representative of a real production environment located in Queensland, Australia. Given the model is provably NP-hard, solution times are seen to quickly become infeasibly large for practical use, motivating the development of heuristic solution techniques.

A constructive heuristic was developed, and two metaheuristics in simulated annealing and tabu search were adapted to obtain good solution schedules quickly. The performance of the metaheuristics was tested using the same random problem instances used to benchmark the performance of the MIP. Solutions were assessed based on algorithm runtime and the relative quality of the resulting schedules. The best results in terms of solution quality were generally obtained by simulated annealing.

Keywords: *Rotomoulding, rotational moulding, production scheduling, batching*

Improving analytical quality assurance in support of current operations

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Abstract: A key challenge in providing OA support to current military operations is ensuring quality analytical outcomes within a high tempo environment that requires results to be produced within short timeframes in order to be relevant for decision makers. Theses short timeframes often mean that the peer review process used for longer term OA studies is not appropriate when providing support to current operations. We propose a new model that consists of a series of layers that, when combined, provide assurance that analysis conducted in support of urgent operations meets an acceptable level of quality. The model also aims to provide decision makers with a better understanding of the quality of the analysis provided to them in order to help them determine how the analysis should be used.

The first layer within the model is to ensure that all aspiring OA staff are provided with training in a known and accepted set of OA skills relevant for current operations. While there are many OA courses offered by various institutions, the Joint Pre-deployment OA Course (JPOAC) run by JOAD provides students with skills and experience expressly tailored for urgent operational environments.

An evaluation and selection process is then applied to determine individuals have the right skills and temperament for OA positions on operations. JPOAC provides a unique opportunity to view and assess potential OA staff in a high pressure environment that is designed to replicate life in an operational HQ.

While working in a military operational environment, analysts have access to a repository of accredited tools and techniques maintained by JOAD staff. This repository consists of fully developed analysis support applications (both custom developed and third party applications) that have been accredited for use on operations as well as software libraries that provide commonly used functions. Additions to the repository can only be made after they pass an accreditation process which involves the thorough testing of the application or library.

Any analysis conducted in an operational environment should adhere to a set of guidelines which have been shown to provide the best foundation for good OA studies. Examples include adhering to established OA best practice or software development standards and guidelines. JOAD has developed an OA code of best practice which has been tailored by Theatre Operations Analysis STC for use in current operations.

Finally, while peer review of analysis is unable to be conducted prior to delivery, we propose conducting a post-delivery review. If the review finds the study was not conducted appropriately, there may still be time for corrective action to be taken. At the very least, analysts can learn from the post-delivery review and lessons can be identified for future similar studies.

This model has been partly implemented and we will provide examples of scenarios where the model has demonstrated its utility, even while in an immature state, to provide quality outcomes to ADF decision makers on current operations.

Keywords: *Quality assurance, current operations, operations analysis*

Scheduling pilot training for 725 Squadron

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Abstract: In this talk, we present a Mixed-Integer Linear Programming (MILP) formulation for a highly complex pilot training scheduling and assignment problem for The 725 Squadron (SQN). The 725 SQN problem concerns a set of students from different cohorts. Each cohort has a different set of lessons that the students in the cohort should complete as much as possible. Each lesson can be delivered repeated in a number of sessions. The number of these sessions required and the time at which they are scheduled are both part of the decisions to be made. Lessons may have different resource requirements in terms of equipment (e.g., a computer, a flight simulator, or an aircraft) and instructors (different instructors have different skill levels, and a lesson can only be taught by qualified instructors). Each lesson contains a subset of the following four phases: Preparation, Briefing, Main Event and Debriefing. Each lesson is taught by one instructor who is required to run all phases of the lesson. However, physical resources are only required for the main phase of a lesson. The main phase requires at most one physical resource.

The basic scheduling and allocation problem is to schedule the times for the sessions of each lesson with the objective of maximizing the number of lessons done by a set of students while satisfying the resource constraints, and the assignment of students to each lesson session. However, the problem under study is far more complicated. There are a set of "paired lessons" that require a pilot student and an Aviation Warfare Officer (an AvWO student) in each session. However, a sandbag may be used in paired lessons meaning that staff members or even other students can be used to cover for one of the students so the other student could take the lesson. On top of that, there are different sets of lessons that can be combined to form a new lesson which we call a "double bubble". Each pair of lessons in the same set can be combined to make a double bubble. In a double bubble, the preparation, briefing and debriefing are carried out only once such that only one instructor is used to teach the combined lessons. The two main events, however, are carried out one after another.

We present a MILP formulation that captures all the business requirements such as setup times, and discuss solution methodologies for solving large-scale problems in a timely manner.

Keywords: *Scheduling, Resource Allocation, Combinatorial Optimization, Integer Programming*

EXTENDED ABSTRACT ONLY

Optimisation of school infrastructure investment

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Abstract: Australia is experiencing significant demographic changes that are affecting the demand pattern for schools. In the last few years there has been an increase in demand in certain areas, so it has become necessary to rationalise investments in new infrastructure and the redevelopment of existing facilities.

To maximise the impact of these investments, it is instructive to develop a decision-making tool that can help answer the following questions: *what schools or extensions should be built? when should they be built? and where should they be built?* While answering these questions, many requirements and constraints should be satisfied, such as building enough schools to provide service to a changing population, intended coverage and capacity of the facilities, as well as trying to satisfy the stakeholders' preferred policies related to the management of their own resources. To illustrate, it is estimated[1] that there will be a 21% growth in student numbers in NSW in 2031 respect to 2018, which translates into accommodating an extra 269,000 students, 164,000 of which will be enrolled in the public system, and that 80% of this growth will occur in urban areas of Sydney. To complicate matters, changes in demographics means that this grow does not occur uniformly across all areas.

In this study, we report on the proposed methodology and software, which solves the problem in two phases. Phase 1 selects potential school locations with minimum associated land cost and population coverage based on the concept of *compatibility*, which we define and use to identify the schools that the students living in a given area are most likely to attend. The output of Phase 1, combined with a costing model, is used to feed the optimisation problem in Phase 2, which decides on the best timing and location for redeveloping schools, installing temporary teaching spaces (or demountables) and building new schools. Through a combinatorial optimisation model, Phase 2 answers the question *where and when should investments in school capacity go in order to minimise the cost of meeting demand?* This is not a trivial question, since demand is not uniform and shows a complex spatial pattern, with varying rates of growth.

We provide an overview of the software, covering input and output data, as well as a summary of the results for Sydney and the Hunter Region (including Newcastle). The results for Sydney suggest the construction of 26 new primary schools, as well as 142 redevelopments, most of which occur at the beginning of the time horizon. The results also show that the existing built capacity of secondary schools is more than enough, so the model does not recommend additional interventions. The results are also consistent with the demand forecasts, as the optimisation model suggests the construction of more new schools near districts with high maximum expected demands. In summary, the optimisation models provide a sensible solution and incorporate all the relevant data and assumptions provided, so that the optimal interventions can be executed in a timely and efficient manner.

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[1] https://www.schoolinfrastructure.nsw.gov.au/about-us/The-school-infrastructure-challenge.html,

accessed on 3 of January 2019.

Keywords: *Facility location, school infrastructure, investment optimisation, demand forecast, planning*

A mixed-integer linear programming approach for soft graph clustering

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Abstract: Many real-life complex systems can be represented by a graph where the vertices, edges, and weights on vertices and/or edges can be used to describe the structural and functional properties of the system, for ex-ample, social networks, the network of word associations, molecular-biological network of protein-protein interactions, and so on. One key aspect of studying these complex systems is to identify communities (or, clusters).

Consider an undirected graph $G = (V, E)$ with V the set of vertices and $E = \{(i, j) \mid i, j \in V, i < j\}$ the set of edges. Each edge $e \in E$ is associated with a weight $w_e \in \mathbb{R}$ that indicates the similarity between its two end vertices–the larger the weight, the more "similar" the two vertices are. The hard graph clustering (HGC) problem is to create distinct partitions (clusters, or, communities) of the set of vertices according to their similarities, i.e., to form $V_1, \ldots, V_k$, where $\bigcup_{i=1,\ldots,k} V_i = V$, and $V_i \cap V_j = \emptyset$ for all $i, j \in \{1, \ldots, k\}$, $i \neq j$.

The soft graph clustering (SGC) problem, on the other hand, allows clusters to have overlaps. A vertex may be a member of more than one cluster. There are numerous applications of SGC, such as: brain research, social network research, natural language processing, citation, and collaboration networks, and so on. Given different applications of the SGC, the objectives and constraints of different SGC applications may vary.

In this talk, we present a Mixed-Integer Linear Programming (MILP) approach for Soft Graph Clustering. Previous methods such as CFinder of Palla et al. (2005) and MaxMax Algorithm of Hope and Keller (2013) are heuristic approaches and can handle problem instances of very large scale. There is, however, no proven performance guarantee. MILP approaches, on other hand, can provide a proven gap when executed under a time limit, and an optimal solution when given sufficient computation time and memory. Although, with existing technology, there is a limit in the size of problem it can handle. Nevertheless, an exact algorithm can be used as a tool for measuring the performance of heuristic approaches by comparing problem instances of moderate sizes and providing a proven gap.

Our MILP model is polynomial in size, and will simultaneously determine the composition of the clusters and allocates membership fraction for vertices that lie in overlapped clusters. Further, we are able to model additional constraints such as imposing a bound on the size of the overlaps or maintaining an equal balance for the total memberships over all clusters. We implement the MILP using IBM ILOG CPLEX on a number of KKI instances as well as a set of synthetic instances with different parameter settings from a random problem generator. We use the latter to study the impact of parameter variation on solution computation time.

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Keywords: *Soft graph clustering, Integer Programming*

A mixed-integer linear programming model for capacitated asset protection problem

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Abstract: Recently due to the existence of bushfire prevention programs such as the implementation of fire danger rating systems and prescribed burning activities as well as early emergency evacuation plans, the number of dead and injured people caused by those incidents decreased over the past ten years in Australia. Disaster management is a tough task and requires a massive amount of money to protect people and communities. The total cost of each event includes but not limited to operational activities, resource expenses and insurance of damaged properties. In Australia, fire and emergency management agencies are responsible for the first response to bushfires. The main objective of bushfire management is to reduce the consequences and impact of emergencies on people, communities, properties and industry. The operational activities won't be successful without having an appropriate responding plan considering all constraints like resource limitation. Incident management teams decide how to distribute available resources. Therefore the human error is an unavoidable part of each operation and could be even worse under the time pressure. Each responding plan must indicate how to allocate resources in an efficient manner while some constraints like lack of resources would cause a significant c risis. To address this complexity, we introduce capacitated asset protection problem in which a set of vehicles with specific capacity must dispatch to protect people and infrastructures over the impacted area. We define the priority of protection for each asset, e .g. houses, schools, workplaces and bridges based on different scenarios. We assume a set of nodes $N = \{1, 2, ..., n\}$ with a specific reward ψ_i, $i = \{1, 2, ..., n\}$, which refers to the priority of protection is given. Several vehicles $Q = \{1, 2, ..., q\}$ from different types $V = \{V_1, V2, V_3, ..., V_p\}$ are required for asset protection that all of them start and end the route at the depot. Due to fire movements, we define a protection requirements $Ri = \{r_1, r_2, ..., r_p\}$ of each vehicle type which is needed to save the asset. The objective function seeks to maximise the total rewards ψ_i collected. Rewards collection at each asset requires a synchronisation visit by different types of vehicles that they must accomplish a task within a specific time window $[O_i, C - i]$. Each vehicle needs a particular time S_i at each node to complete a job, and once it is free, it can continue its journey. Although one of the key-challenges for firefighters on the ground is the lack of water during the operation, we take the capacity of vehicles C_q into account. One must consider reloading at the nearest reloading station like lakes or rivers if there is sufficient time for travelling and refilling. Otherwise, the vehicle must return to depot and no longer is able to protect any other asset. The proposed model ensures that time window is never violated for different scenarios, e.g. from one node to another node, one node to a warehouse or vice versa. The designed model is formulated in forms of the mixed-integer linear programming model and is NP-hard. Initially, the problem was implemented for Python 3.7 and solved using ILOG CPLEX 12.8.0. We designed a set of 25 assets which needs to be protected by three types of vehicles. CPLEX needs more than an hour to solve the problem, which is not applicable for operational purposes. To overcome this challenge, we propose adaptive large neighbourhood search to solve a capacitated asset protection problem with time windows and synchronisation constraints. The computational results suggest that the developed model and generated algorithm will be a useful decision-aid incident managers.

Keywords: *Bushfire, asset protection problem, vehicle routing problem, time window*

Sequence Analysis Applying Fuzzy Graph Theory and Fuzzy Core Index Method in Social Network Analysis

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Abstract: Fuzzy information such as human behavior and cognition can be represented by fuzzy graph. In general, the information structure is very complicated and it is difficult to interpret the characteristics of the graph. One of the remaining challenges is its sequence analysis among nodes of the fuzzy graph. In other words, the analysis to obtain the totally ordered set in the graph. This challenge is important issue for instruction design process in instruction analysis and for relation structure analysis in sociometry analysis and so on. For example, in teaching material structure analysis, it is important to consider the order of teaching. Also, in sociometry analysis for elementary school students, it is very important for creating a communication network. If we have information about the network, it will help us to predict the propagation path when someone catches a cold. As to this problem, Nishida et al. proposed an One-Sided Connectivity Method. This method considers the sequencing problem based on the α cut. In general, this ordering structure may be a partially orderd set. and we couldn't sequence nodes totally in Fuzzy graph. Matsui et al. introduced the method applying GA (Genetic Algorithm) and fuzzy reasoning. These method could be analyzed for the sequencing problem using the linear model. We proposed a Fuzzy Core Index (hereinafter called "FCI") Method based on fuzzy core value. Generally, applying this method, the ordering structure would be totally orderd set. We showed the effectiveness of this proposed method through the case study.

At first, we would introduce the new index "fuzzy core index" for sequence analysis. Secondly, we would discuss the relationship between AHP (Analytic Hierarchy Process) method and characteristic analysis of fuzzy graph concerning the fuzzy core index. Finally, we would show the effectiveness of this proposed method through the social network analysis focusing on the fuzzy sociometry analysis which can not assume the transitive law. The sociometry analysis developed by Moreno is one of the measurement and evaluation methods of social structure which we could analyze by applying the fuzzy graph theory. According to the data obtained from some simple questionnaires, we can measure the preferring degree among the members of a group and obtain the fuzzy sociogram. Here, indicator FCI that can measure the importance of members in a group can analyze the social structure more effectively just because we can rate the members based on the indicator.

1	1.00	0.56	0.96	0.73	0.84
0.68	1	0.37	0.95	0.49	0.62
1.00	1.00	1	1.00	0.94	0.96
0.63	0.93	0.35	1	0.43	0.59
0.98	1.00	0.72	0.90	1	0.74
0.94	1.00	0.60	1.00	0.62	1

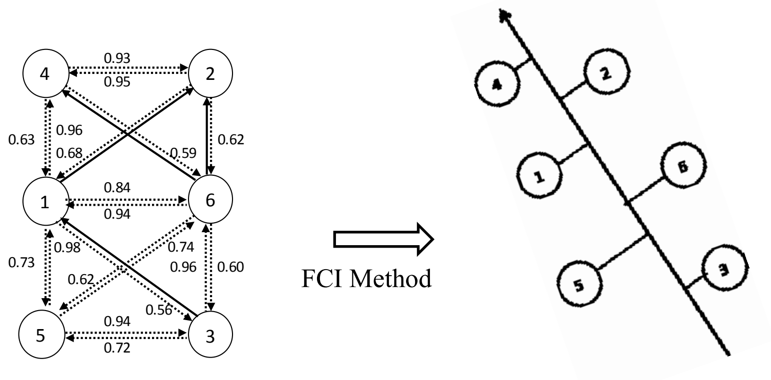

Figure 1. Framework of FCI Method : conversion from partially ordered set to totally ordered set

Keywords: *Fuzzy Graph, Sequence Analysis, Fuzzy Core Index Method, Analytic Hierarchy Process, Sociometry Analysis*

A branch-and-cut algorithm and valid inequalities for the covering Chinese postman problem

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Abstract: We propose a combinatorial optimization problem called covering Chinese postman problem (CCPP). The CCPP is a generalization of the rural postman problem which is one of the representative arc routing problems. Consider an undirected graph $G(V,E)$ with cost $c(u,v) : E \to \mathbb{R}^+$ and covering $D(u,v) : E \to \mathcal{P}(E)$ functions on the edges, where $P(E)$ is the power set of the set of edges E. The objective of CCPP is to find a minimum cost tour such that the edges visited by the tour cover all the edges of the network. In other words, the union of covering sets $D(u,v)$ for all edges (u,v) in the tour should be the set of edges E of the graph. This problem can be shown NP-hard by reduction from the well known travelling salesman problem (TSP). Let each customer in TSP be represented in CCPP by one edge (u,v) with zero cost and covered exclusively by itself (customer edge); now let the edges connecting two customers in TSP (inter-customer edges) to be in CCPP connecting the corresponding pair of customer edges with the same cost. Finally, consider that inter-customer edges are all covered by any edge of the network.

Figures 1 and 2 give two examples of solutions for CCPP. In Figure 1 all edges have one unit of cost and the covering function for each edge $(u,v) \in E$ is defined as the set of edges that are incident to either the nodes u or v. Figure 2 shows a solution for the same graph and costs but defining the covering function of each edge $(u,v) \in E$ as all edges whose both incident nodes are at most from three units of distance from both u and v.

Some of the CCPP applications include automated meter reading and disaster planning. In the case of automated meter reading, utility companies employ wireless powered meter readers to read utility meters from a distance. This way the meter reader does not need to visit every street of the network but rather a subset of them which covers all customers. The aim is to find the minimum cost route that is able to read all customers.

Our contribution. An integer programming formulation and an associated branch-and-cut algorithm are proposed for the CCPP. We also proposed two sets of valid inequalities and an associated separation algorithm. The valid inequalities are shown to substantially improve the branch-and-cut algorithm performance. Computational experiments were performed with six sets of benchmark instances of up to 597 nodes and 1526 edges. The branch-and-cut algorithm was able to obtain 326 optimal solutions out of a total of 390 instances without the valid inequalities, and 355 optimal solutions with the valid inequalities. Moreover, we show some patterns related to covering functions that make them more difficult to be solved by the proposed methods.

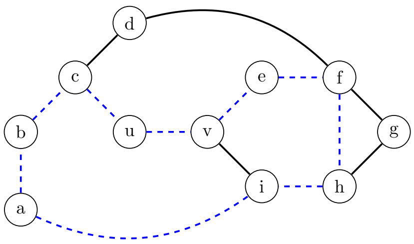

Figure 1. Example of a CCPP instance and its solution.

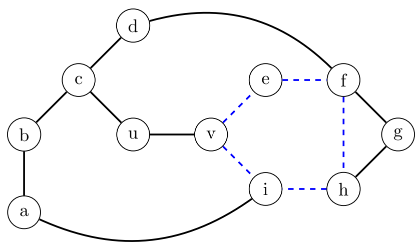

Figure 2. Example of a CCPP instance with a wider covering function and its solution.

Keywords: *Arc routing, separation algorithm, integer programming, combinatorial optimization*

Modelling railway traffic management through multi-agent systems and reinforcement learning

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Abstract: Australia plays a significant role in the world's coal supply. The world's largest coal operation is located in the state of New South Wales, where more than 87% of the transport is done through railways. One of the strategies to increase throughput is to use sophisticated computational techniques for train scheduling optimisation and this study applies artificial intelligence techniques to the railway traffic management problem in the context of the Hunter Valley Coal Chain Coordinator (HVCCC). This problem has been studied mostly through centralised decision-making models, applying linear integer programming, heuristics and hybrid approaches. However, recent publications indicate a lack of practical applications (Lamorgese et al. [2018]), pointing out that low computational requirements, scalability, decentralisation and real-world commitment are key features required for deployment-ready applications.

Towards that, one option is to model system actors (trains, stations, dispatchers, operators, and more) as autonomous intelligent agents that interact, learn and act independently to reach their own objectives – thus constituting a multi-agent system (MAS). This way, the railway traffic system will be capable of making rapid, distributed decisions. Few studies have modelled railway traffic management as a MAS and they lack many of the important decisions, constraints and actors present in real-world scenarios (Lamorgese et al. [2018]).

This paper describes a discrete event simulation model of a small, closed railway, and implements a decentralised and heterogeneous MAS for train dispatching. The model was built using the Arena Simulation Software[1]. It includes several train agents and a single dispatcher agent that applies different decision methods (First-in-First-Out rule, random walk and reinforcement learning) to regulate railway traffic decisions.

The paper describes how experiments were designed, computational results, calibration of the reinforcement learning (RL) algorithm, performance tests for various levels of congestion, and tests for transfer learning between different instance configurations. The RL performance outperforms the FIFO standard dispatch rule by 10.3% for the high-congestion network configuration. In addition, transfer learning tests illustrate the generalisation capability of the RL method, where knowledge gained during the training using an instance reduces the time required for the training of additional instances. This represents an initial step towards the application of the approach in the HVCCC network traffic management problem.

[1] https://www.arenasimulation.com/

Keywords: *Railway traffic management, multi-agent systems, reinforcement learning, transfer learning, discrete event simulation*

Flow balancing in a wastewater network by optimising storage in pumping stations

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Abstract: We have an urban wastewater conveyance and treatment network that requires the assets to cope with the peak system loading, even if for just a brief period of time per day. This results in an underutilised asset base, and unbalanced inflow into the treatment plant; the latter results in suboptimal conditions for the systems that treat the water. We propose to use the vast, existing wastewater network and reticulation as an 'equalizer tank' in order to smooth the demand at the treatment plant. The purpose is to achieve improved performance of our existing assets without further investment. In this paper, we describe a proof-of-concept algorithm to demonstrate the ability to control the diurnal load pattern of wastewater conveyance in a live network, along with results from a live pilot.

The benefits of such capability are two-fold: potential deferral of capital investment for asset upgrades, and improved operating conditions and costs. Equaliser tanks are commonly used to both improve operating conditions at the treatment plant and to provide a mechanism to control high volume events. However, these benefits could be achieved using the network itself. By controlling the flow and effectively flattening it across the day, the requirement to handle the peaks in flow diminishes and reduces the need to increase capacity of pipes, pumping stations and the treatment plant itself to meet the peak demand.

The problem of deciding how much flow to permit from each pumping station is fairly trivial. However, in our network setting we only control the pumping station flow indirectly via level set-points in the well. That is, the pump will only activate when the water reaches a cut-in set-point, and will stop pumping when the water reaches the cut-out set-point. The pump rate is usually fixed-speed, and is not expected to change during or between pump cycles. Additionally, we have only indirect measurement of the flow itself, either by the hours of pumping and pumping rates or by the levels and pumping times. Furthermore, the control system is limited to 12 settings per day and 4 settings per year, restricting us to a static solution for a stochastic problem.

In this paper we present an algorithm for obtaining a complete network set-point solution in efficient runtime. The algorithm guarantees finding feasible solutions when they exist, and is guided by the optimal solution for the deterministic version of the problem. We have modelled the wastewater network in a hydrology modelling tool which provides some basic simulation functionality. We present the results of a pilot we conducted on a subset of our wastewater network. We monitor asset performance and H_2S levels and report the differences. We demonstrate that flattening of the diurnal curve is possible to achieve in a controlled manner.

Keywords: *Wastewater flow balancing, equalising, optimisation, dynamic algorithm, stochastic*

The network maintenance problem on an arc with uncapacitated repair

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Abstract: The network maintenance problem is motivated by the need to maintain infrastructure networks over time. We consider networks in which a commodity is transported between origin-destination pairs, and at the same time the infrastructure assets need to be maintained by resources moving in the network. In order to perform maintenance the assets have to be shut down thus reducing the system capacity. The objective is to maximise the total throughput by aligning the maintenance activities efficiently. In this paper, we study a special case of the network maintenance problem where the network consists of a single arc connecting an origin to a destination. Furthermore, there is no restriction on the amount of repair if the resource is to perform maintenance in a time period.

This problem is of interest for the following reasons. Firstly, it generalises variants of the lot-sizing problem and the warehouse problem, both of which have been well-studied in the literature. Secondly, we hope that understanding this special case will be useful in tackling more general variants of the network maintenance problem.

In this paper, we present a mixed integer linear programming formulation. We then show that a special class of feasible solutions, called *Maximum Flow Order Up* (MFOU) solutions, contains at least one optimal solution. Based on this result, we introduce an alternative integer linear programming formulation with only five decision variables. As a consequence, the optimal objective function value for any instance of the problem can be obtained in polynomial time.

Keywords: *Network maintenance, mixed integer linear programming, scheduling, polynomial time*

Optimised long term forestry planning considering increasing wildfire risk

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Abstract: In long-term forestry supply chain planning, where the scope is large areas of established plantations and existing forest-product manufacturing networks, the most important decisions are the assignments of tree species and end-products to plantations, and the assignment of plantations' end-products to mills and customers. The former infers how the crop is tended over time via actions such as pruning and thinning, as well as the distribution of years over which crop maturity can be expected. Wildfire degrades or destroys forest crops. Whereas in the past the crop-loss effect of wildfire could be neglected in a milder-climate country such as Chile, this is no longer the case. Wildfire sizes and intensities are increasing, and this is reducing the mean time between fires for plantations (i.e., the *return rate*). Many thousands of hectares of forestry plantation were lost to wildfire in Chile in early 2017, and this has had substantial negative effects for available wood volumes in the forestry supply chain stretching many years into the future.

To account for wildfire in long-term forestry planning, we need to estimate the future occurrence, extent and intensity of wildfires for a set of regions for which forestry planning decisions are sought. In this, it is the long-term effect that is of interest, not the forecasting of specific future events. To do this requires an analysis of weather and fire impact history, past and future fire likelihood estimation, and a large experimental program of wildfire numerical simulations that can shed light on the extent and intensity of future wildfires. The analysis and simulation must be spatially explicit, because there is much local and regional variation in meteorology, forest fuels, topography and the locations of plantation assets. Climate change effects need to be represented by way of scenarios about the proportion of high fire danger days experienced in future, and scenarios are also needed pertaining to future firefighting effectiveness.

For an optimisation-based approach to long term forestry planning, the estimates of future occurrence, extent and intensity of wildfires lead to coefficients and other input data for optimisation models. We adapt a practically-successful and well-established LP-based model with a multi-decadal time horizon, adding variables and constraints associated with wildfire effects. The addition of wildfire considerations requires new constraints affecting the stock of plantation at each point in time, the replanting of land, and application of harvest equipment. Data analysis and optimisation solution results demonstrate that the main outcome of (spatially varying) increases in fire frequency on optimal forestry plans is that there is a tendency to shift faster-maturing crop into areas that have greater fire return-rates (i.e., more frequent fires), with the risk of crop loss due to fire increasingly overriding considerations of logistical efficiency and forest productivity. This is an expected result, but nevertheless is one which implies industry-wide shifts in the spatial distributions of species and forest-product manufacturing. It also motivates consideration of new optimisation problems in which plantation-species-product assignments and production supply chain infrastructure are co-optimised over time.

Keywords: *Supply chain planning, forestry, wildfire, linear programming*

Mixed integer linear programming for the minimum-sum-of-squares clustering

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Abstract: Cluster analysis refers to the general class of problems in which a set of objects or data points are divided into a number of groups (clusters) such that the objects in the same group are more similar to each other than to those in the other groups. Clustering is a subclass of unsupervised machine learning with many applications. The minimum-sum-of-squares clustering (MSSC) is one of the most important problems in this context. This problem can be represented as a combinatorial optimization problem as follows:

Given a set of N data points, $\mathcal{N} = \{1, \ldots, N\}$, the number of clusters, K, and the squared Euclidean distance d_{ij} between data points $i, j \in \mathcal{N}$, find a partition of $\mathcal{N}$ denoted by $\mathcal{C}_1, \ldots, \mathcal{C}_K$ such that the total variance defined by $\sum_{k=1}^{K} \sum_{i \in \mathcal{C}_k} \sum_{j \in \mathcal{C}_k} \frac{d_{ij}}{2|\mathcal{C}_k|}$ is minimized. Here $|\mathcal{C}_k| = n_k$ represents the number of objects in cluster k which is a decision variable. This implies that the objective function is non-linear. However, this is a linear-fractional objective function and therefore the problem can be solved by transforming it into an equivalent linear formulation.

The MSSC problem is NP-hard even if n_k is given a priori (Rujeerapaiboon et al., 2019). This includes problem instances with only $K = 2$ clusters. The special case of the problem in which $n_1 = \cdots = n_K \geq 3$ is also shown to be NP-complete (Pyatkin et al., 2017). In this study, we explore the capability of modern Mixed Integer Linear Programming (MILP) solvers to solve this challenging problem to optimality. We consider the general case of the problem in which n_k is not given a priori.

In our talk, we first present an overview of the existing mathematical programming formulations for the MSSC problem. We then introduce new formulations for the problem that employ a polynomial number of decision variables. Some of these formulations use an exponential number of constraints. Therefore, we propose a branch and cut approach to solve them. We discuss how these formulations can be improved to obtain a faster convergence. We report results of a computational study to compare the formulations.

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Keywords: *Cluster analysis, minimum-sum-of-squares, integer linear programming*

The influence of the vendor's power on vendor-retailer partnerships

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Abstract: The literature on vendor-retailer relationship mostly considers two extreme cases. The first case is when all the decision related to managing the inventory of the retailer are made by the retailer, i.e., RMI (Retailer Managed Inventory). The second case is when all of those decisions are made by the vendor, i.e., VMI (Vendor Managed Inventory). In this study, we introduce a concept of power which relates to a vendor's ability to alter (within some constraints) the retailer's decisions. We develop some mathematical models for this new type of partnership and characterise the vendor and the retailer's optimal decisions. We show how the concept of power could help to fill the gap between RMI and VMI as extreme models. For some specific cases of interest, we identify the optimal (in terms of overall supply chain cost) balance of power between the retailer and the vendor. Our analysis shows that, for a case where the demand is constant, the optimal balance of power between the retailer and the vendor permits the vendor to change the schedules of the orders. Our numerical study reveals that this type of partnership performs better in an environment with low demand volatility. We also analyse the case where the vendor aims to optimise the total supply chain cost. For the class of system considered, we show that if the power is not sufficient to alter order timing, then there is no improvement compared to RMI.

Keywords: *Supply chain coordination, vendor managed inventory, lot-sizing*

A simple heuristic for the coupled task scheduling problem

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Abstract: The coupled task scheduling problem deals with the problem of scheduling a set of jobs to be processed on a single machine. Each job consists of two separated tasks where the second task of a job must be started after the completion of its first task plus a predefined exact delay time. We study the coupled task scheduling problem with the objective of minimising the maximum completion time, i.e., the makespan. The problem is known to be strongly NP-hard. We propose a simple heuristic for the problem. The heuristic sets the midpoint of given lower and upper bounds as a makespan and solves a feasibility problem. Upon solving the feasibility problem the upper bound is updated to the midpoint. Otherwise, the lower bound is updated to the midpoint. The algorithm keeps iterating until the bound interval is zero. Computational experiments indicate that the proposed heuristic outperforms the exact solver.

Keywords: *Heuristic search, feasibility, makespan, scheduling*

EXTENDED ABSTRACT ONLY

A spatial decomposition based Math-heuristic approach to the asset protection problem

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Abstract: This work addresses the highly critical task of planning asset protection activities during uncontrollable wildfires known in the literature as the Asset Protection Problem (APP). In the APP each asset requires a protective service to be performed by a set of emergency response vehicles within a specific time period defined by the spread of fire. Each asset may require a mix of vehicles, such as tankers, pumpers, and aerial vehicles. The capabilities of vehicles visiting an asset must meet the asset requirements. Each asset has an associated value of importance, which determines their priority in planning.

We propose a new spatial decomposition based Math-heuristic approach to the solution of large-scale APPs. The heuristic exploits the property that time windows are geographically correlated as fire spreads across a landscape. Thus an appropriate division of the landscape allows the problem to be decomposed into smaller more tractable sub-problems. The main challenge then is to minimise the difference between the final locations of vehicles from one division to the optimal starting locations of the next division. This involves biasing the solution of a current stage towards a target direction that will mean vehicles are in locations suitable for a good start of servicing assets in the next stage.

The performance of the proposed approach is tested on a set of benchmark instances from the literature and compared to the most recent Adaptive Large Neighborhood Search (ALNS) algorithm developed for the APP. The results show that our proposed solution approach outperforms the ALNS algorithm on all instances with comparable computation time. We also see a trend with the margin of outperformance becoming more significant as the problems get larger. The scalability of our method together with the use of a standard commercial solver means that new situations can be modelled quickly and solved efficiently within times suitable for operational purposes. The proposed approach is applicable to similar problems where the time-windows are correlated with a direction. This is the case for evacuation problems during certain flood events, for example, or the advance of an attacking armed force.

Keywords: *Wildfires, asset protection problem, emergency response vehicles, Math-heuristic, spatial decomposition*

A heuristic for the generalized due-date min-max earliness-tardiness problem

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Abstract: We study a single machine scheduling problem with generalized due-dates (GDD) with the goal of minimizing the maximum earliness-tardiness. Under the assumption of GDD the due-dates are not job-dependent but rather associated with the number of jobs previously processed. We develop an efficient heuristic for the problem. We compare the heuristic and the well-known shortest processing time (SPT) and longest processing time (LPT) dispatching rules, as well as a random rule. The extensive numerical tests indicate that the heuristic performs very well.

Keywords: *Single machine, earliness, tardiness, generalized due-dates, heuristic*

Cluster-First, Route-Second Approach to Capacitated VRP Problems

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Abstract: The Vehicle Routing Problem (VRP) consists of finding optimal routes for a fleet of vehicles in order to serve a number of customers situated at various locations. This is well-known to be an NP-hard combinatorial optimisation problem. For most practical applications, which involve instances of larger sizes, finding good solutions within a reasonable computation time becomes a very challenging task.

In this communication we propose a novel methodology to solve VRP problems, by using a divide-and-conquer approach. In a first step, we seek to identify clusters of customers, such that each cluster is to be served by a single vehicle. Then, a classical routing algorithm is applied to each cluster. The first step of our methodology is a generalisation of K-means, where additional capacity constraints are imposed on the clusters. We devise an efficient technique for building the clusters, which trims down the search and thus leads to computational efficiency. We test our novel methodology on standard datasets from the literature, including very challenging instances where the supply demand exceeds 95% of the available loading capacity.

Figure 1. Comparative illustration of allocations of customers to routes, where the convex hulls of the routes are highlighted. They correspond to VRP solutions obtained using the *Indigo* solver (left image) and our proposed cluster building method (right image), on an instance where the total demand is 97% of the available capacity. Our fast method leads to routes that are only 5% longer, have smaller convex hulls and exhibit better mutual separation.

We compare our proposed method against the state-of-the-art solver *Indigo*, which uses a classical combinatorial optimisation technique based on Adaptive Large Neighbourhood Search (ALNS). We present experimental results that show that our method has substantially better computational efficiency, with only a small increase in total route length. We also show that our proposed method leads to VRP solutions with more compact and better separated routes. These are features that are appreciated by logistics managers, as they allow for quick and simple alterations in response to unforeseen last-minute events.

Keywords: *Vehicle Routing Problem, Combinatorial Optimisation, Clustering, K-Means*

Intelligent Analyst Assistant: Identifying and visualising causal events to support closed-loop combat simulation analysis

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Abstract: Closed-loop stochastic combat simulations can approximate the operational effectiveness of military alternatives with the aim of providing insights to decision-makers. Here, alternatives may be physical, such as different platforms or terrain conditions, or behavioural, such as tactics, techniques or procedures. This simulation analysis is typically conducted using end-of-run output data, which whilst valid, is limited in its inability to robustly explain the underlying reasons behind end-of-run findings. Three key challenges need overcoming to address the end-of-run analysis limitations: 1) the limited ability to identify and explain outliers within a set of replications and to determine if they are genuine results, an artefact of the model, or invalid replications that should be removed; 2) the limited ability to explain key differences between groups of replications - either different groups within the same alternative or groups from different alternatives; and 3) the inability to describe the *narrative* of the simulation - more specifically, to describe the evolution of the simulation in terms of key events and how these events shape the end outcome. This presentation details research between DST Group and Deakin University in addressing these challenges. A case study provides context for the analytical techniques developed, and other analysis methods that warrant further exploration are proposed. In the case study, a Blue combat team attack scenario was modelled in *COMBAT XXI* to compare three different vehicle options: A, B and C. The primary objective of Blue was the rapid seizure of an urban fringe area, while the opposing Red team's objective was to delay Blue from doing so by 24 hours.

A software suite was developed that systematically applies visualisation and analysis techniques to the case study simulation data. The software suite specialises in analysing intra-run data; that is, data that describe the evolution over time of the simulation. Intra-run data is essential in establishing links between key events that occur throughout the simulation replication and the final outcome. In this presentation, a number of techniques are described, and their effectiveness is assessed by applying them to the case study. The techniques belong to six broad theme areas: 1) end-of-run metric analysis; 2) intra-run metric analysis; 3) temporal predictor analysis; 4) hierarchical clustering; 5) geospatial analysis; and 6) probabilistic graphical models. A key outcome of this research is the belief that the developed software suite and its initial collection of visualisation and analysis algorithms constitute a precursor to the Intelligent Analyst Assistant. This assistant will become a synthetic collaborative agent that will complement and enhance an analysts capabilities in the future of combat simulation analysis. Each algorithm within the assistant will offer a unique perspective, producing key visualisations or performing various analyses, designed to find key events, correlations, trends and patterns. The assisted analysts will then combine the results and construct the *simulation narrative*. In combat simulation analysis, it is crucial that once an insight is found, it can be communicated to simulation developers, analysts and decision-makers. An effective way to understand and communicate complexity is through narratives. A primary functionality for the Intelligent Analyst Assistant is to aid the analyst in creating such a narrative and to identify insights that can be effectively communicated. Ideally, the Intelligent Analyst Assistant will make it possible to find pieces of the narrative puzzle scattered throughout the simulation data landscape which the analysts will then piece together in order to provide robust explanations to decision-makers. During this research this has been observed with the developed software suite, whereby subject matter experts and senior/junior analysts have discovered interesting insights not possible using only the end-of-run analysis techniques.

Keywords: *Combat simulation, causal events, simulation narrative, visual analytics*

Two common pitfalls applying design of experiments (and hopefully how to avoid them!)

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Abstract: The Defence Science and Technology Group, as part of their Modelling Complex Warfighting Strategic Research Investment, has been developing a prototype simulation depicting joint warfighting. The Joint Future OpeRating Concept Explorer (JFORCE) is an agent-based, stochastic simulation, where the parameters define the physical attributes of the entities, control their behaviour, or define a particular scenario. The Design of Experiments (DOE) is a structured investigation through this high-dimensional parameter-space and the simulation's stochastic response in order to support a particular analytical objective. Characterising the form and strength of the sensitivity of the simulation's response to changes to factor settings can provide insight into sub-system/attribute contributions to joint warfighting operational effectiveness and the trade-space between them. This paper sets out to highlight two of the more common pitfalls analysts might face when conducting such a sensitivity analysis of stochastic simulations.

Regression fits a model $\hat{y}(\mathbf{x}, \hat{\boldsymbol{\beta}})$ where the coefficients $\hat{\boldsymbol{\beta}}$ (which reflect the sensitivity of the parameters) are chosen to make the model close to the simulation response at a number of user-specified design points and replications. A very common choice is to consider a *baseline* scenario and other scenarios where only one parameter is changed at a time. This *One Factor At a Time* (OFAT) design intuitively makes sense, but it's a trap for new players. The second issue is that some regression software generally assume that the simulation responses at the design points are *independent and identically distributed* (iid), which allows the analysis to be conducted using common (and simpler) *Analysis of Variance* (ANOVA) procedures. But for simulations that employ *common random numbers* the assumption of independence is not met (by design) and the assumption of identically distributed simulation responses at each of the design points can often be found wanting. The aim of this paper is to convince the reader to avoid the temptation to use OFAT designs and to be cautious when using DOE software that rely on iid assumptions.

Now, one should consider the fitted regression coefficients as a point estimate of a random variable $\hat{\mathbf{B}}$, which ideally should have the properties of minimum bias $(\min |E[\hat{\mathbf{B}}] - \boldsymbol{\beta}|)$ and maximum precision $(\min var[\hat{\mathbf{B}}])$. A simple example using the JFORCE simulation will hopefully be sufficient to demonstrate the negative implications of relying on OFAT designs and/or iid assumptions. First, it will be shown that the OFAT design contains more bias than an equivalent sized superior design, as well as suffering false negatives (two of three sensitive parameters were not picked up as such). Secondly, even when using this superior design, the iid assumptions will be shown to either under-estimate or over-estimate the regression coefficient confidence intervals, potentially causing false positives (claiming a sensitive parameter when it is not).

The first pitfall (OFAT design) can be avoided if one reads just about any text on DOE. However, one of the classic texts, and some DOE software packages, still espouse the use of traditional ANOVA, thus making avoiding the second pitfall (iid assumptions) less easy for practitioners. This paper, by detailing the required mathematical formulation and illustrating through a small but typical example, potentially offers a useful path forward.

Keywords: *Design of experiments, combat simulation, independent and identically distributed, bias, precision*

Simulation design and analysis to support decision making in the management of capability programs

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Abstract: This paper discusses a study into the initial application of Design of Experiments (DOE)-based sensitivity analysis to low-fidelity simulation of Program-level capability scenarios, in order to provide statistical robustness to evidence, and greater confidence to early-stage decision making. The following excerpt from Hallett et al. (2018) provides the context surrounding scenario modelling work from which this study is motivated:

> *Following the 2016 First Principles Review, Defence introduced an updated Capability Life Cycle and a Program Management construct to develop and manage Defence Capabilities for the Joint Force. Conventional wisdom holds that to realise the potential of the Joint Force and the capabilities that support it, careful analysis of the capabilities and their integration and interoperability is required. Programs are a step towards more formally managing the complex capabilities and their integration and interoperability demands and are in addition to the [existing] Project/Product level management.*
>
> *The Joint Capability Narrative, the Joint Capability Needs Statement, the Program Strategy, and the Program Integrating Operational Concept are elements that provide a top-down driven understanding of what a capability must achieve, where it needs to operate, and with whom it needs to operate. The central theme of all these elements can be portrayed in a set of scenarios covering the operation and support of the capability.*

An evidence base for decisions is essential. Hallett et al. (2018) explain that "demands on the Defence budget put pressure on Programs to provide robust capability-based business cases" to support decision makers, and that "[t]he business case should include new Project justification". Foundationally for this study, Jusaitis & Cook (2018) demonstrate how supporting evidence "can be derived from analysis of the current and proposed capabilities in Program scenarios against an agreed set of Program Measures of Effectiveness".

Hallett et al. (2018) describe and propose an executable model-based approach to Program scenario analysis, and Jusaitis & Cook (2018) explore the practical underpinnings of this methodology and discuss the development of a model framework. The framework supports simulation and analysis of Program capability scenarios, to produce first-order estimations of the effectiveness predictions that can demonstrate the feasibility of the capability design.

The executable model examined in this study addresses a straightforward hypothetical air-defence capability scenario. The goal for the initial application of DOE was to define performance envelope boundaries for a defence fighter platform intercepting a range of attacking opponent platforms. In preparation for DOE, the model was designed to receive fourteen input factors and to provide six output responses. Responses were captured as durations at select events during each simulation. A Nearly Orthogonal Latin Hypercube Design was applied together with factor screening statistical analysis to inform the removal of non-significant factors and support selection of a response-of-interest. This was followed by a full-factorial design focussed on the remaining factors with a regression analysis to inform selection of significant factors for response optimisation. Finally, sensitivity analysis was run to understand which significant factor combinations provided optimal responses; these factors were then used to define the boundaries of fighter performance envelopes against various opponent platforms.

Analysis of the performance boundaries for an existing hostile capability against those of a predicted future hostile capability provided insight into the capability gaps to retain capability overmatch with a future opponent. This result demonstrates that DOE offers a valid and useful approach to providing a level of statistical robustness to the analysis of low-fidelity capability scenarios.

Keywords: *Executable architecture, operational architecture, design of experiments, capability design*

EXTENDED ABSTRACT ONLY

Factor screening high-dimensional, stochastic combat simulations

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Abstract: High-fidelity combat simulations often use many equations in an attempt to describe accurately the physical and behavioural phenomena under study. However, in practice, it is often the case that only a few factors of these overly-parameterised simulations have a substantial influence on the simulated response. This assumed parsimony principle (or Occam's razor) implies an early desire to screen out those factors which have negligible influence on the system's behaviour, so that subsequent analysis can focus on those that matter. In this paper, we explore some useful methods for factor screening based on popular predictive models such as LASSO (least absolute shrinkage and selection operator), Gaussian Process (GP), and Random Forest (RF). LASSO is a linear regression model coupled with regularization to reduce the likelihood of overfitting. Bayesian LASSO extends this by placing the conditional Laplace prior on the coefficient vector. The popularity of modeling a black-box function (e.g., simulation) with a GP is attributed to the tractability of its posterior distribution. A common kernel function used in GP modeling is the squared exponential, also known as Automatic Relevance Determination (ARD), as it has the capacity to fit different length-scales to each factor. When these length-scales are properly estimated from data, they can be indicative of the degree of non-linearity of the response with respect to the factors. However, these length-scales cannot separate out different degrees of linear effects. An alternative to ARD is to use Kullback-Leibler (KL)-divergence between a training point and its perturbation in one factor as a measurement of predictive relevance. KL-divergence is a popular method to quantify the difference between two probability distributions. For non-continuous response metrics (e.g., the combat winner), RF is a popular choice. The importance of a factor for predicting the response is estimated by aggregating the weighted impurity decrease for all nodes where that factor is used, averaged over all trees in the forest. This is the most popular way of measuring factor importance with RF, where the importance is measured by predictive relevance, rather than the sensitivity of the response.

A prototype simulation depicting joint warfighting has been developed by the Defence Science and Technology Group as part of their Modelling Complex Warfighting Strategic Research Investment and was used to test the approaches above. We screened 34 real-valued factors (asset speeds, sensor/weapon ranges, and munition performances) for their influence on the probability that the Blue Force wins. Data to fit the various approaches were iteratively generated using Bayesian optimization. We first randomly initialize 35 data points (each replicated 200 times) and then use batched Thompson sampling to suggest the next set of 20 data points (again with 200 replications), with the goal of maximizing the probability that Blue Force wins. To examine the convergence rate of the methods, we generated 90 batches, resulting in $35 + (1 + 90) \times 20 = 1855 \times 200$ individual data points.

Only a small number (3 to 5) of the 34 factors had a substantial effect on the simulation response. LASSO, Bayesian LASSO and RF produced largely similar results, while GP with ARD and GP with KL-divergence were also similar to each other. All models produced nearly equivalent mean squared errors. For the top five influential factors, all screening methods included Red and Blue aircraft sensor ranges, and Red ground-based air defence weapon range, and all but one included Blue's air-to-ground missile kill probability. Note that the GP with ARD identified factors that indicated likely non-linear dependence with the probability of winning. While this study has explored factor screening methods as proof-of-concept, it remains to be seen which techniques scale more favourably with increasing numbers of factors (i.e., in the order of hundreds of factors) as this is where the majority of high-fidelity (production) combat simulations reside. To enable this, we envisage further exploiting the sequential/adaptive nature of simulation designs of experiments. In doing so, we hope to reduce the dimensionality of the factor-space by iteratively declaring factors as sensitive/insensitive as sufficient evidence is generated, thereby curtailing the otherwise combinatorial data requirements.

Keywords: *Factor screening, combat simulation, Bayesian optimization*

Development of a disaster evacuation tool using SUMO

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Abstract: According to the Aquaduct Global Flood Analyzer, the global cost of flooding annually is currently estimated to be $96 billion in GDP and is forecasted to increase more than five times to $521 billion by 2030. Poor countries in Asia would be hit hardest, with India as most vulnerable, followed by Bangladesh, Vietnam, Pakistan and Indonesia. The numbers of people impacted by floods around the world could nearly triple to 54 million by 2030, driven in part by climate change and unchecked development. In Australia, the cost of natural disasters is forecasted to quadruple from $6.3 billion a year currently to about $23 billion a year by 2050, according to German reinsurer Munich RE. The soaring cost is driven largely by Australia's increasing population density and the increasing frequency and severity of storms, floods, cyclones and bushfires. However, investment in preventative measures could mitigate the impact of disasters and reduce government expenditure by more than 50 percent. The Australian government currently spends around $560 million annually on disaster response and recovery compared to $50 million a year on planning and prevention. The National Institute of Building Sciences estimates that governments can save as much as $11 in response cost for every $1 invested in planning and mitigation.

Evacuation planning, one of the suite of tasks under emergency planning and response, pertains to the urgent movement of people away from an area that contains an imminent threat towards an area of safety, hopefully conducted as quickly and efficiently as possible. It is an extremely difficult task involving perhaps tens of thousands of people and vehicles, where the number of evacuees (demand) can easily overwhelm the road network (supply) leading to disastrous consequences. This problem is only likely to get worse as populations continue to increase, while road infrastructure deteriorates, and network capacities remain static.

Given a disaster scenario, the appropriate evacuation plan prevents casualties and minimises the evacuation time by balancing supply and demand in the road network in order to avoid congestion. Through the use of virtual agents that reproduce network traffic in extreme events, simulation has been shown to be one of the most effective ways to evaluate and compare evacuation plans. This paper describes the development of a decision support tool for emergency evacuation using the SUMO software. SUMO (Simulation of Urban Mobility) is an agent-based traffic simulator that facilitates the modelling of intermodal traffic systems containing various agents such as pedestrians, road vehicles and public transport.

The evacuation tool simulates the implementation of an evacuation plan over a road network including components such as the target population, schedules of departures, primary and alternative destination points, and modified or closed road links. With each simulation run, the tool collects statistics and measures of performance for the evacuation plan under the given disaster scenario. The analysis of simulation results can then identify the suburbs with longest evacuation times, the locations of potential bottlenecks, the overloaded links and routes, and the overcrowded destination points. The tool can quickly simulate and evaluate the performance of different evacuation plans under thousands of disaster scenarios using a parallel computing environment. In the short-term, this will identify which evacuation plans will work best under which disaster scenarios. In the long-term, the tool can aid in investment and resource planning, providing local government with the science-based evidence to support decisions, such as whether to spend limited funds in widening a road link, strengthening a bridge, or in buying more fire trucks.

The paper also presents and discusses the results of the application of the evacuation tool on a bushfire scenario in the Otways region of Victoria and on a flooding scenario in the Hawkesbury Region of New South Wales. The conclusions will provide insight into the applicability of SUMO as a simulation engine for evacuation modelling as well as potential future work and improvements on the decision support tool.

Keywords: *Agent based simulation, disaster planning, emergency management, scenario evaluation*

Investigating the use of uninhabited aerial systems (UAS) to support anti-ship missile defence through simulations

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Abstract: The Australian Government is concerned with the increasing threat presented by ballistic and cruise missiles, which was acknowledged in the 2016 Defence White Paper. In response to the rise and spread of missile technology, there is significant interest in understanding missile defence options which can be used to protect our deployed forces.

The transition towards deploying autonomous systems across Defence has occurred rapidly, which is reflected in the 2016 Defence Integrated Investment Program. Uninhabited aerial systems (UAS) are commonly used to provide surveillance, reconnaissance, and protection of Defence assets, and are increasingly utilised within the missile defence domain.

In this study, we have applied modelling and simulation-based analyses to explore how different UAS concepts can be implemented in concert with other platforms to enhance an anti-ship missile defence (ASMD) capability. The discrete-time, constructive simulation environment allowed for the integration of different blue and red system models, and for the end-to-end kill chain performance of those models to be evaluated. For the purpose of our research, we have used unclassified generic models which are indicative of their class of system. Within this environment, we simulated UAS dedicated to providing third-party targeting to naval surface combatants engaged in ASMD scenarios. A range of generic UAS classes equipped with different sensor suites and deployed in various formations and numbers were modelled against a range of threat approach angles, threat speeds and threat multiplicities, and the improvements in ASMD detection timelines and engagement performance were assessed. Design of Experiment (DoE) techniques were applied to make an informed selection of the simulations to be performed to maximise the computational resources available to perform the large number of simulations necessary to cover the solution space. The outcome of the study was an assessment of the relative merit of different UAS "concepts" (combinations of the sensor suites, numbers and formations) and their effectiveness in improving the ASMD performance.

Keywords: *Missile defence, simulation, uninhabited aerial system, uninhabited aerial vehicle, design of experiments*

Modelling a multi-modal logistic network with agents and dynamic graphs

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Abstract: This paper presents a model of a logistic system. Our goal is to understand how such a system (with numerous stakeholders) behaves and evolves according to different constraints or scenarios. We adopted a complex system approach which leads us to propose an agent-based model coupled with dynamic graphs. It allows us to represent the properties, constraints and behaviours at a local level of a logistic system in order to reproduce the global behaviours thanks to the simulation in a dynamic context. The simulation (which uses data about the Seine axis) allows to test different scenarios in order to understand how local decisions impact the whole system. For example, this work presents the evolution of the system at the opening of the Seine–Nord Europe Canal. Indeed, this canal is a real major project for Europe, and has numerous economical stakes. So, we first describe the traffic evolution on the multi-modal transportation network (see figures 1 to 4). Then, we observe different other measures (evolution of costs, transportation mode share). Thanks to these analyses, we show that the Seine-Nord Europe Canal should promote the use of the river barges and reduce financial costs. In the same time, it could modify the respective shares of the northern European ports.

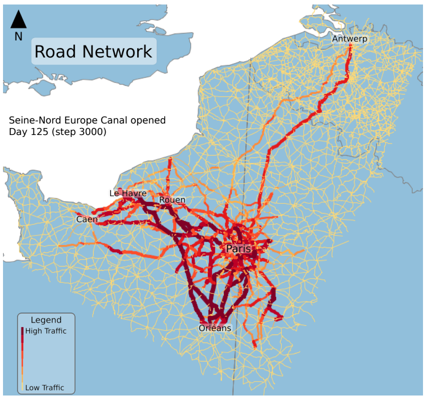

Figure 1. Road traffic (day 125) - Seine-Nord Europe Canal is opened.

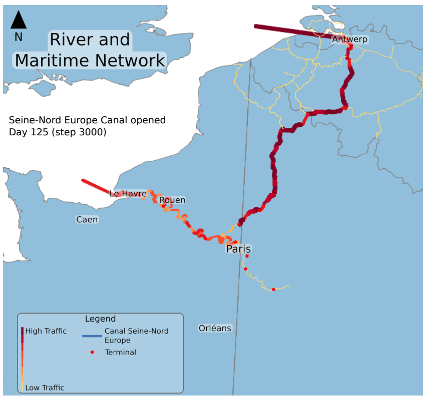

Figure 2. River traffic (day 125) - Seine-Nord Europe Canal is opened.

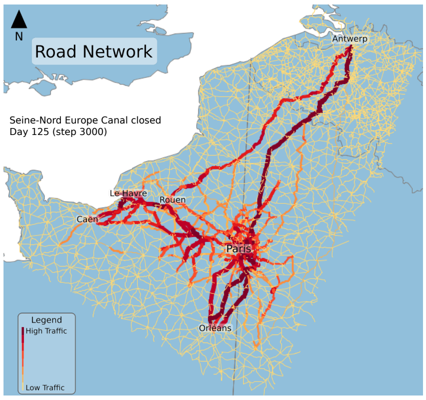

Figure 3. Road traffic (day 125) - Seine-Nord Europe Canal is closed.

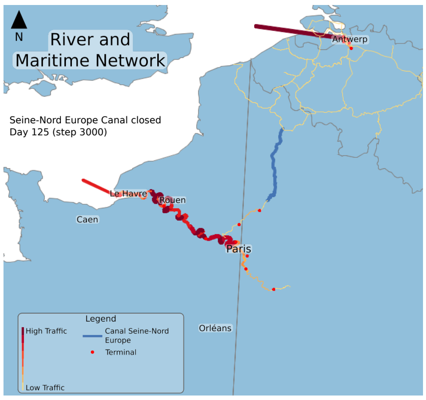

Figure 4. River traffic (day 125) - Seine-Nord Europe Canal is closed.

Keywords: *Agent-based model, dynamic graph, complex system, logistic system, adaptive behaviour*

EXTENDED ABSTRACT ONLY

Helicopter (blue) agent path optimisation against small-arms operators

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Abstract: The focus of this work is helicopter (blue) agent path optimisation to minimise vulnerability against small-arms operators on the ground while ensuring fastest time to destination. The proposed optimisation method employs generalised regression neural network (GRNN) agents for shooters, developed using human-in-the-loop experiments. The shooter agent provides accurate generalisation of statistical models for 19 discrete firing positions used in the experiments to arbitrary shooter positions. A probability-of-hit analysis is carried out to predict the vulnerability of the helicopter in a variety of situations based on the trained shooter agent. A probability-of-hit map is constructed to predict and quantify the vulnerability of the blue agent to shooter agent positions. Based on these probability-of-hit maps, tactical strategies are developed and implemented to realise optimal blue agent manoeuvres.

A red artificial intelligence (AI) agent representing the shooter is trained using nine parameters derived from the statistical estimates of closest point of approach (CPA) data at 19 shooter positions (see Fig. 1). The trial data were obtained for four different helicopter manoeuvres: ascending, descending, low-altitude slow speed, and high-altitude fast speed. The ANN agent generates CPA statistics, viz., mean vector and covariance matrix, for any given firing position within a semi-circle of radius 500 m when the helicopter is at the centre of the circle (which coincides with the origin of the coordinate system), heading north. CPA data are modelled as trivariate Gaussian random vectors. The linear projectile assumption and the significant difference between projectile and helicopter speeds implies that CPAs will be approximately distributed on a 2D plane in the 3D space. A set of probability-of-hit maps were computed using the red agents for different environmental conditions (e.g., day vs night) and whether tracer is used or not. The analysis of the probability-of-hit maps led to important conclusions as regards optimal shooter angles with respect to helicopter heading that maximise the probability of hitting the helicopter and characterisation of shooting positions with almost zero hit probabilities.

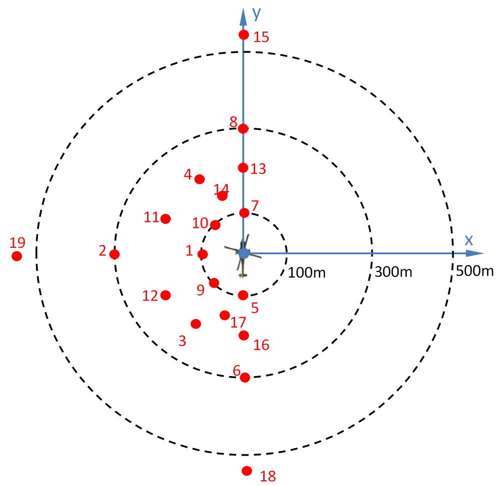

Figure 1. Shooter positions with respect to helicopter in the human-in-the loop experiments.

Optimal flight paths for the helicopter were computed based on the objectives of shortest time to destination and minimising the likelihood of getting hit by a shooter at a known position. The joint optimisation of these two criteria was achieved using heading angles and convex combination of two cost functions with a single weight parameter controlling the priority of each criterion.

The developed blue agent optimisation strategy is sufficiently general and can be modified to take account of constraints (e.g., no-fly zones), random shooter positions with Bayesian prior, and 6-DOF helicopter flight dynamics.

Keywords: *Path optimisation, generalised regression neural networks, dynamic error probable*

An Integrated Platform System Model (IPSM) applied to a large Unmanned Underwater Vehicle (UUV) for design and mission planning decision support

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Abstract: IPSM is a set of tools suitable for application to a wide variety of physical and logical systems modelling. It marries state-of-the-art a-causal symbolic model definitions built in the Modelica language to open source software scripting and management tools, creating a highly re-configurable and easily re-purposed 'digital twin'. This paper reports the outcomes from recent early investigation of large UUV's, considering their performance under conditions of uncertainty using a strict mathematical definition for Measure of Effectiveness ($0 <= \text{MoE} <= 1$)[1] that is design independent.[2] This approach removes the need to evaluate utility, a common and difficult step in decision theory, using instead ratios of probability under anticipated uncertainty to evaluate and compare decisions in both design and operation. We discuss optimal choices faced during design and operation of the UUV when faced with a mission, and the robustness of such choices using large scale Monte Carlo analyses. Currently these types of analyses can prove useful in supporting decision making at the design and acquisition stages of procurement, and this paper concludes they have significant utility for managing risk, by evaluating all branches and sequels typically encountered by operators during mission planning[3]. An example of the approach is applied to an Echo Voyager Extra Large UUV (XLUUV) undertaking a long range mission.

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Keywords: *Decision making, exploratory modelling, simulation-based optimization, robust choice*

An assessment of the accuracy of military workforce models

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Abstract: This paper describes work performed to assess the accuracy of a typical military workforce model used by the Australian Defence Organisation (ADO), and by many other military organisations, to forecast future workforce composition. While there are many published accounts describing such model construction, the author has found little evidence of work done to assess the accuracy of the models described.

The military workforce is predominantly a closed system. Recruits enter at the lowest rank and then over time move to higher ranks or leave the system. How long it takes to gain a promotion is determined by: access to training and skill acquisition; personal aptitude; imposed limits on the numbers allowed in a rank; set minimum times individuals have to spend in each rank; and whether individuals choose to promote. The main influences on the workforce system are then: the annual separation numbers; how long people take to promote from one rank to another; the annual numbers of recruits; and the composition of the starting population. From estimates of separation numbers and promotion times, workforce models can be used to evaluate recruiting plans in meeting desired future workforce numbers.

To perform the desired assessment, a model was constructed in a form that enabled it to replicate the operation of the type of model used by the ADO. The model, which is described in more detail in the body of this report, uses an entity based formulation constructed in the ARENA simulation modelling tool. The model constructed was then run using actual data for both annual separation numbers and monthly recruit intakes to determine if it could accurately replicate the targeted workforce system. The data used was collected from personnel records collected between 2003 and 2016. The initial results established that the model is a reasonable representation of reality. To test the model as it is used in practice, further forecasts were made using estimates of annual separation numbers. Typically, ADO modellers use historical average separation numbers and promotion times as inputs to their models, and so, this approach was trialled in this assessment. Additionally, some more dynamic time series based estimates were tested to see if they could improve model accuracy.

From the tests described, the following findings were made.

1. The model performs well when actual historical data is used.
2. Good estimates of promotion times can be made using common probability distribution functions and that these provide a means to assess any uncertainty in the model's results.
3. When using the historical average number of separations as inputs to the model, the model can perform poorly. For example for a rank attained only by the more skilled in the workforce, and thus of more interest to forecasters, the average error for the estimated population size when using the historical average for the separation number input is approximately 15% and the maximum error 35%. When actual data is used the error is 4% and 17%, respectively.
4. Separation number estimates using more complicated time series calculations, when tested, showed that these may be a means, in some circumstances, to provide more accurate and precise workforce forecasts than can be produced using the historical average.

Keywords: *Military workforce planning, simulation modelling, validation, stochastic modelling*

Modelling drought impacts on coffee production in Viet Nam: A system dynamics approach

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Abstract: Viet Nam is the world's largest producer of Robusta coffee, accounting for more than 40% of global Robusta output. Coffee production contributes to about 10% of agricultural export turnover in the country and supports the livelihoods of approximately half a million smallholder farmers. However, coffee cultivation faces numerous challenges, particularly drought and water shortages driven by changing climate conditions and unsustainable agricultural practices.

Using a system dynamics approach, our study aims to assess the major impacts of drought affecting sustainable coffee production in Dak Lak Province, a key coffee growing region responsible for more than 30% of Viet Nam's coffee output. A dynamic hypothesis (causal loop diagram) was formulated based on literature review and qualitative data from interviews with 60 coffee farmers and experts to capture the interrelationships and feedbacks among factors relating to drought impacts on coffee production.

Mapping these relationships to produce the causal loop diagram indicates that the consequences of drought on coffee cultivation are an outcome of complex interactions between the climate system and human systems, specifically population growth, deforestation and agricultural development. Key factors driving drought impacts on coffee production are declining rainfall in the dry season, increasing coffee expansion and over-irrigation, which interact with other factors, such as rising temperature and evapotranspiration, through reinforcing and balancing feedback loops. The impact of drought on coffee yield and coffee quality mainly depends on drought severity and supplemental ground and surface water availability.

Our analysis highlights several systems archetypes, including *'tragedy of the commons'* and *'limits to growth'*, associated with overuse of regional common resources, triggered by uncontrollable agricultural expansion and water exploitation, particularly of groundwater for irrigation. The unintentional outcomes of a number of management decisions or policies (indicated through the *'fixes that fails'* systems archetype)—such as the planned migration program which has led to population growth and deforestation, contributing to declining water availability—are also analysed. The monoculture cropping system of Robusta coffee also has undesirable consequences, including increasing vulnerability of the coffee system to changing climate and market risks such as price volatility.

A suite of management strategies is proposed including awareness raising and promotion of technologies and policy measures on efficient water use for irrigation, sustainable planning for coffee development, livelihood diversification, agroforestry either through intercropping or shading, and forest protection, reforestation and afforestation.

An initial simulation model based on these results is in progress for robust quantification of drought impacts and for the design and testing of various policy interventions for sustainable coffee production.

Keywords: *Causal loop diagrams, system dynamics, drought impact assessment, adaptation*

Bayesian Network meta-models from combat simulation for Defence decision analysis

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Abstract: Defence Science and Technology Group (DST) is investigating the characteristics of Land Combat Vehicles (LCVs) with a view to improving purchasing decisions between different LCV options. Using a combination of closed-loop combat simulation (i.e., one run without any human interventions) and subject matter experts (SMEs), these studies seek to understand the close combat capability factors for a future LCV. These factors are being investigated for different kinds of physical environment and different levels of enemy lethality, with each LCV's lethality, survivability, signature (the ease with which the enemy identifies friendly forces) and knowledge acquisition (friendly forces identifying enemies) being measured, yielding a multi-dimensional view of the different LCVs and their performance. Our study describes a new approach, developing a Bayesian network (BN) meta-model (i.e., a model based upon the combat simulation model; see Fig 1) that combines those multiple dimensions in a single multicriterial decision model.

Both deterministic and stochastic methods have been developed for multicriteria decision analysis (MCDA). Limitations to prior approaches include treating utilities as independent of each other and also very limited ability to deal with uncertainty about preferences. Bayesian networks offer advantages in these regards, so here we develop an alternative approach using a BN meta-model for decision making and evaluating the operational impact of different LCV choices. BNs support both the prediction of operational results and their causal explanation. These BNs were developed both from expert elicitation and causal discovery (data mining) from combat simulation data, and enable causal visualization, sensitivity analysis and optimization. We evaluate the performance of some of these BNs against alternatives, using common accuracy-based evaluation metrics. Please note that the example and data presented in this paper are not representative of the real LCV options and testing scenario, they are used for methodology illustration only.

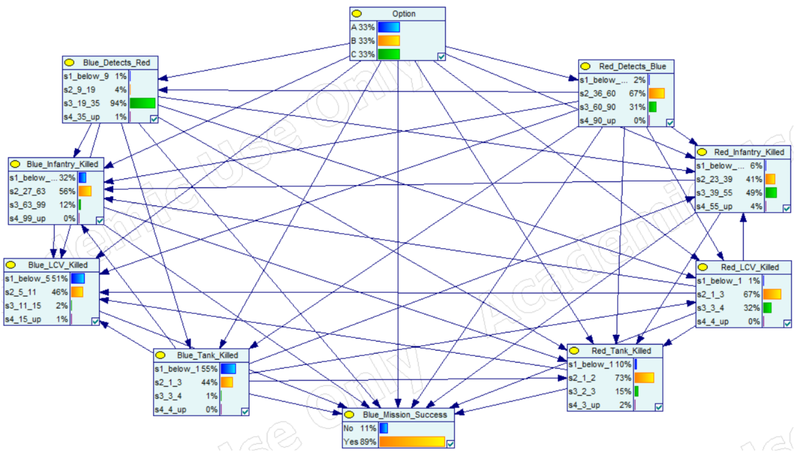

Figure 1. A Bayesian network meta-model (from the PC algorithm).

Keywords: *Bayesian network modelling, multicriteria decision analysis, combat simulation and model evaluation*

Repair priorities in repairable spare part supply systems: a simulation-optimization approach

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Abstract: Industries employing expensive assets maintain extensive repair facility operations and keep spare stocks. This type of logistics system, where both forward and reverse logistics systems are required, in addition to repair facilities, is known as a repairable system. We study a repairable spare part supply system consisting of one repair facility and one stock point, where repairables are kept on the stock to serve expensive capital assets in order to prevent downtime.

We set up the objective of our model to minimize the expected total inventory holding costs of spare parts and costs for the downtime of assets over an infinite horizon. In this study, we particularly analyze the effect of static repair priorities on the expected total cost. To achieve this, we seek optimal values of the repairable spare parts stocks and the assignment of different repairable types into priority classes.

We model the repair facility as a multi-server multi-class queue, where failed repairable parts are repaired based on priority classes. It is generally difficult to analyze this type of queuing systems with analytical methods even for a small size problem with the limited number of priority classes and repairable types. Therefore to alleviate this difficulty, we develop a two-stage sequential simulation-optimization algorithm. In the first stage, the set of all feasible priority assignments is searched by a Genetic Algorithm (GA) meta-heuristic to find an assignment that achieves the minimum cost. In the second stage, a discrete event simulation (DES) is run for the given priority assignment provided by the GA to analyze the multi-class multi-server queueing model. The probability distribution for the number of failed spare parts in the repair facility is obtained as an output of the DES. We use probability distributions to calculate the optimal level of repairable spare part stocks to keep in the inventory.

We compare the performance of the simulation-optimization algorithm with a First-Come First-Served (FCFS) service discipline since FCFS reflects the common way of working in practice. The conducted computational experiments show that the proposed approach yields a significant amount of total cost reduction in some extreme cases reaching up to 90%.

Keywords: *Repairable parts, repair priority, simulation-optimization, genetic algorithm*

A hybrid immersed boundary–lattice Boltzmann and finite difference method for bushfire simulation

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Abstract: Catastrophic bushfire that destroys the assets and multiple facilities happened many times all over the world in the last two decades. The majority of the most damaging fires involve wind and terrain, in order to predict the spread process of bushfire in various geographical and weather conditions, a hybrid numerical method is proposed for bushfire simulation. The outputs from the numerical simulation of bushfire can be used to guide the extinguishment process and improve the security. The present numerical method includes three parts: fluid solver, heat transfer solver, and immersed boundary method for fluid–structure interaction and heat transfer. Specifically, the multi-relaxation time lattice Boltzmann method is adopted for the dynamics of non-Newtonian flow, with sub-grid viscosity model for large eddy simulation, a geometry-adaptive technique to enhance the computational efficiency and immersed boundary method to achieve no-slip boundary conditions. The heat transfer equation is spatially discretized by a second-order up-wind scheme for the convection term, a central difference scheme for the diffusion term, and a second-order difference scheme for the temporal term. The major contribution of this work is the integration of spatial adaptivity, thermal finite difference method, and fluid flow immersed boundary-lattice Boltzmann method. Several benchmark cases including power-law fluid flow and heat transfer around a stationary cylinder and flow around a stationary sphere are used to validate the present method and developed solver. The good agreements achieved by the present method with the published data indicate that the present extension is an efficient way for fluid–structure interaction and heat transfer in fluid flow. In addition, a demonstration considering bushfire–wind–terrain interaction is presented.

Keywords: *Immersed boundary method, lattice-Boltzmann method, heat transfer, bushfire simulation*

EXTENDED ABSTRACT ONLY

AgPasture – a general pasture model for APSIM Next Generation

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Abstract: Seventy percent of the world's agricultural area is fully or partially covered in grasslands. These grasslands provide food for animals to convert into meat, milk, fibre, draft power and many other secondary products so farming systems simulation models must include options for this vegetation type. We here describe the conversion and adaptation of AgPasture, a model for pastoral species, into APSIM Next Generation.

AgPasture has its origins in the 1990s with the physiological models of Thornley and Johnson, the SGS/DairyMod/EcoMod models, and an earlier version of APSIM (version 7.x) in the early 2000s. Although based on those models, several changes have been made to enable AgPasture's integration into APSIM Next Generation and to incorporate new functionalities to describe plant physiology and its interactions with the environment. These improvements include a complete rewrite into APSIM-compliant C#, addition of new processes to account for the effect of reproductive status on root-shoot partitioning, luxury N uptake, reallocation of tissue nitrogen reserves and to discriminate root systems for individual species in the simulation of mixed swards. The general approach of AgPasture is that it considers one or more species that have separate plant components (Figure 1). The sward dynamics is modelled through pools that differ according to tissue senescence (Figure 1). These pools are considered for the simulation of harvests and the addition of organic matter to the soil as plant litter or via root senescence.

As with all plant simulation models, validation is challenging. Validation of pasture models is more complex than that of annual crops because their perennial nature means that there is no annual reset of the plant; pasture mass is difficult to quantify at practical measurement scales due to large spatial variability; most field data is both water and nutrient limited with the limitations often not measured *in situ*; and the measurements are inevitably affected by some combination of senescence and grazing. The data used for the validation of AgPasture is the most comprehensive national dataset on pasture growth in New Zealand. However, it was collected before reliable weather data was available, which makes comparisons on a timeseries basis unrealistic. Even though this adds to the list of challenges intrinsic to the simulation of pastoral systems, it does not make the task of simulating such systems insurmountable. Here we present the model and our approach to the validation of the data despite the challenging circumstances.

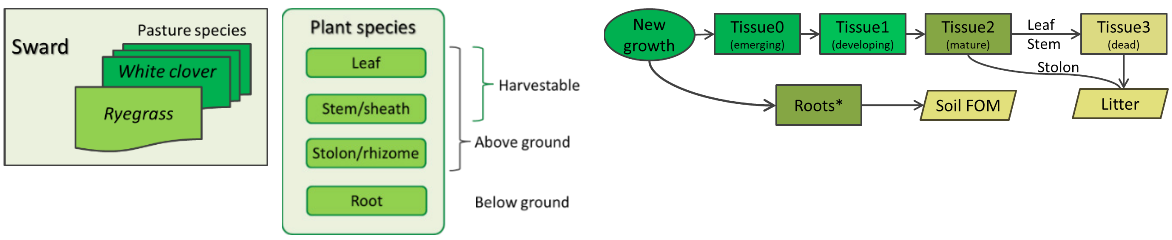

Figure 1. AgPasture manages a sward based on one or more species (left), which have their own separate plant components (centre). These age through several stages, considered as tissue pools, before a harvest event or its addition to the soil as plant litter (right). *Roots only have one tissue pool.

Keywords: *Dynamic simulation model, gross photosynthesis, respiration, water balance, nitrogen balance*

Using pedotransfer functions to improve the precision of spatially predicted available water capacity

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Abstract: Knowledge about soil water is critical for dryland agriculture. The amount of plant available water (PAW) is important for crop management decisions such as whether to sow or not, choice of crop or variety and addition of fertilizer. Understanding the variation of the available water capacity (AWC) of soil through the landscape can be achieved by using spatial modelling techniques such as Digital Soil Mapping (DSM). DSM predictions of AWC can be done outright using point data from field sites or with pedotransfer functions (PTFs) that use other modelled soil attributes as inputs. DSM methods allow for the inclusion of the prediction uncertainties associated with modelled datasets. One technique to account for these uncertainties is to use Latin Hypercube sampling in PTF predictions to generate multiple bounded realisations of the input data.

The Soil and Landscape Grid of Australia (SLGA) provides AWC as a soil attribute that was produced using depth-harmonized point data and formal DSM methods. The aim of this paper was to test whether AWC can be modelled with greater precision by using the more reliably-predicted soil attributes such as clay and sand percentage as input parameters to PTFs. The evaluation was over the six standard *GlobalSoilMap* depths.

To evaluate the precision of the modelled AWC datasets, the SLGA AWC mean value, 90% Prediction Interval (90% PI) and (for the 0-1 m depth aggregation) standard deviation datasets were compared with three PTF-derived AWC predictions across a study area covering the grain growing regions of Queensland and NSW. The differences in each grid cell were averaged across the study area and then normalised by the thickness of the depth layer.

The general trend for all three PTF-derived AWC datasets is to predict smaller mean AWC values than the SLGA AWC for the study area, albeit with some differences between them. In all cases the predictions had greater precision than the SLGA AWC. That is, the 90% PI is smaller for the PTF-derived AWC datasets compared to the SLGA AWC, and this difference is consistent going down the soil profile to 1 m.

The results presented here show that it is likely that modelling AWC using PTFs will give a more precise prediction of AWC than the methods attempting to predict AWC outright, like those which produced the SLGA AWC. One reason for this is that there is limited field-measured point data available to use when modelling AWC directly. Further work will include an assessment of PTF uncertainty and validation of PTF outputs against field-measured AWC to assess the accuracy of the predictions.

Keywords: *Digital soil mapping, pedotransfer function, uncertainty, (plant) available water capacity*

Automated Reasoning for Situational Awareness

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Abstract: The smooth operation of industrial or business enterprises like supply chains, assembly lines or warehouses, critically depends on maintaining situational awareness. Situational awareness is the problem of gathering changes in the operation's environment, aggregating them to derive the current state at a semantically meaningful level, projecting the current state into the near future, alerting the user of potential problems, and proposing corrective action if needed.

Comprehensive situational awareness is indispensable for making good decisions, but building a software system for situational awareness is difficult for several reasons. In the real world one rarely has complete and/or correct observations. Sensor inputs, like that from GPS data is inherently noisy, object recognition from video/photos is unreliable, databases are incomplete or inconsistent, and status reports from human actors can be entirely missing or late, etc. Because of that, situational awareness currently lacks adequate software tool support. While database systems and ERP (Enterprise Resource Planning) systems can help human operators gain situational awareness, they do not offer a complete solution with integrated analytic capabilities based on deeper inferences. One should expect the system to be able to fill in unobserved events, auto-correct erroneous data, retro-fit late observations to explain or re-adjust earlier conclusions, and much more.

We propose a novel approach for achieving these capabilities by exploiting and advancing research from relevant AI areas like diagnosis, planning, temporal logic, and automated reasoning. Our modular architecture integrates algorithms from these areas, tailored for our situational awareness needs, and makes them available through a re-usable modeling language.

The work reported on here builds on the approach proposed by Baumgartner and Haslum (2018). The main difference is the inference engine, which is now based on a combination of *disjunctive logic programming* (with stratified negation) and *belief revision*. This provides us with a declarative modeling language that supports hypothesizing multiple plausible world models and revoking them later based on new information.

The modeling language is made available to the user in an object-oriented setting. As usual, it allows the user to define class hierarchies for specifying objects that share the same properties. As a novel feature, class definitions can contain logic programming rules that are specific to that class' instances and that are partially instantiated at object creation. States, then, are nothing but (time-stamped) collections of objects, and state updates are computed by applying the instances' rules to the current state and currently observed external events. The main benefit of this paradigm is that it combines highly structured (object-oriented) modeling with declarative modeling (logic programming), which is advantegeous in complex domains like supply chains.

Our approach is implemented in the Fusemate system. Fusemate has its origin in a situational awareness and scheduling system for the factory floor of an industrial client, which we generalize to be applicable in a variety of domains. Although each model is application-specific, Fusemate is universal. It is, in essence, a forward-chaining rule engine in an object-oriented setting, realized via a shallow embedding in Scala. The main advantage of this design is that it gives access to the full power of the Scala language to represent process states and express conditions, functions and transformations on them. This provides expressive power and flexibility, at little implementation cost.

In the talk, we will present the modeling paradigm described above, its implementation via shallow encoding, and some practical experiments.

References

Baumgartner, P. and P. Haslum (2018). Situational Awareness for Industrial Operations. In TBA (Ed.), *ASOR-2018 – 26th ASOR National Conference for the Australian Society of Operations Research and Defence Operations Research Symposium (ASOR/DORS) 2018*. Springer.

Keywords: *Situational awareness, automated reasoning, disjunctive logic programming, belief revision*

Comparing remote sensing and tabulated crop coefficients to assess irrigation water use

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Abstract: Agriculture accounts for approximately 72% of water use in Australia. This high volume of water use over many years has led to water sharing plans being implemented in regions of high agricultural activity, such as the Murray Darling Basin. Theoretically, the implementation of water sharing plans provides a sustainable solution for sharing this resource between irrigators, communities and the environment. Although, currently there are minimal options to choose from to monitor water use without visiting sites, which can be time consuming and cost prohibitive. There is a need to monitor the water used by the various stakeholders within the system, to monitor, and regulate, for its long-term success and sustainability.

This paper compares a previously developed approach for monitoring irrigation water use via remote sensing of crop coefficients (K_c), and gridded climate data with a repurposed irrigation scheduling approach, recommended by State Governments in Australia using tabulated K_c and rain gauges (using Food and Agriculture Organisation Paper 56 (FAO56) methodology). The tabulated values have been locally derived, which is often important in accounting for environmental factors which may not occur elsewhere in the world. The remote sensing relationships used were derived in North America over a range of crops, which may introduce errors. Although the remote sensing methodology possesses many benefits as it does not require knowledge of seasonal growth and soil characteristics. The comparisons were performed over an almond orchard in the Northern Adelaide Plains and a vineyard located in the McLaren Vale wine region, both in South Australia.

This study found that the remote sensing approach provided better results for the almond plantation, which is thought to be due to the management of almonds agreeing with hydrological assumptions made during the methodology derivation. Conversely, the vineyard returned better results using the localised tabulated K_c; thought to be due to an induced water stress, a common farming practice used to produce quality fruit and wine products. It is evident that the remote sensing relationships are unable to monitor these management strategies. The sparse canopy cover of wine grape vines may also be contributing to the limitation of the remote sensing methodology.

The remote sensing method has definite advantages compared to using tabulated values as it shows an actual K_c, as opposed to a theoretical K_c, removing the possibility of disease and other non-typical conditions going unnoticed in the tabulated method. The remote sensing method removes the need for modellers to obtain data on planting dates, soil texture/hydraulic characteristics and detailed knowledge of crop type. A tabulated method is likely more difficult from a technical perspective to scale up to a catchment/basin scale extent that covers multiple crop/land use types. Overall, this paper demonstrates that the tabulated K_c method can be used to monitor irrigation on farm scale sites. Although, despite its shortcomings, the use of the remote sensing method allows the simulation to be performed in remote areas where there is little to no in-situ measurements and shows greater ability and potential to be scaled to larger regions.

Keywords: *Irrigation, remote sensing, water accounting, water management*

Representing conservation tillage in agricultural systems simulations

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Abstract: Conservation tillage is defined as a set of soil management practices that aim to minimise mechanical soil disturbance through tillage. Several studies have shown that conservation tillage has many positive effects on soil health, but the magnitude and direction of the impacts on crop productivity and environmental outcomes vary considerably. Tillage practices affect a multitude of factors and processes (e.g. changes in soil physical properties, the amount and distribution of organic matter in the soil, root growth and the availability of water and nutrients to crops) and these are further influenced by complex interactions with climate, soil type, and other management actions specific to each individual production system. The overall impact of tillage management practices on crop productivity and environmental outcomes is thus a combination of many concomitant and relatively weak signals from different components of the soil-plant system. This complexity can, in principle, be disentangled by agricultural systems models that represent the underlying processes in both plants and soils, plus their interactions with climate and management. However, given this complexity, a wide variety of processes and factors need to be represented in the model, and it is unclear how comprehensively this is captured in current state-of-the-art tools. In this work, we present a case-study where two tillage scenarios, "conventional" and "no-till", were parameterised in the Agricultural Production Systems sIMulator (APSIM) model for New Zealand conditions. We tested the model's current 'off-the-shelf' capabilities and explored how variations in the simulation setup plus APSIM-manager scripts can be used to enhance the breadth of representation in tillage effects. The performance of the model and relevance of contrasting input and parameter sets were investigated through sensitivity analysis and by comparing the model results against general responses observed in tillage field trials. Our results highlight current strengths, limitations, and challenges to represent real-world impacts of tillage practices in modelling assessments in general and APSIM in particular. The characterisation of different tillage practices in simulations is often limited and the dynamic nature of soil responses to tillage is not fully captured either. Although new developments in the APSIM model enable implementing some dynamic changes in soil properties, the parameterisation of such process remains a major challenge. Insights on key aspects to be considered when setting up simulations that represent tillage in bio-physical models and areas for future development are discussed.

Keywords: *Tillage, modelling, productivity, environmental impact*

Challenges in modelling multi-species pastoral systems

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Abstract: Increasing the species diversity in grazed pastures has been promoted to improve the performance of pastoral systems. The addition of alternative forage species (e.g. chicory (*Cichorium intybus L.*) or plantain (*Plantago lanceolata L.*)) to traditional pastures (grass and/or grass plus legume, such as ryegrass (*Lolium perenne L.*) and white clover (*Trifolium repens L.*)) can enhance the resilience of some aspects of the production system, reducing the impacts caused by droughts, pest infestations, etc. This should result in an increase in, or at least maintenance of, production levels while improving resource utilisation. Diverse pastures have been found to have more stable yields and produce more balanced feed. A potential positive consequence of this is the reduction in the risk of nutrient losses. However, the introduction of different species can change the pasture's growth pattern compared to traditional swards, this can complicate the management of feed quality and availability along the year. There is, thus, a need to improve our understanding of diverse pastures and of developing tools that can help farm managers to implement and manage such systems. Biophysical models can play an important role in this context: aiding the study of alternative species and their integration into diverse pastures; complementing the analyses from field research studies; and enabling the extrapolation of such analyses to different conditions. Developing and understanding how biophysical models can be used in these tasks is therefore crucial. In this work we use the Agricultural Production System Simulator framework (APSIM) as a case study to review and explore approaches to overcome some of the challenges of modelling diverse pastures.

A basic constraint in this area is the need to develop plant models for the various species. This is not a simple task as data is scarce for many plants, but tools such as APSIM's Plant Modelling Framework (PMF) aid this task. Examples of the use of the PMF in this work include the newly-released APSIM models for chicory, plantain, red clover, and white clover. However, many processes and factors that need to be accounted for when modelling multiple species swards go beyond those needed for the description of plant growth in monocultures. Competition for resources – for light and physical space in the canopy and for nutrients and water in the root system – remains a major issue. Such interactions depend on accounting for the plant's structural development (height and the placement of leaves in the canopy, for example) to an extent that is typically not necessary for monocultures. Moreover, plants can change some of their characteristics as a result of competition (e.g. growing taller or with deeper roots) and they differ in which organs are affected and how much they change. Interactions *via* phytochemicals can also happen, but their relevance and mechanisms are still poorly understood. In pastures, many management actions and animal behaviours can have an impact on the plant community and the relative performance of each species. For instance, fertiliser applications will favour plants such as grasses that can utilise this resource efficiently at the expense of legumes; animals will select highly palatable plants during grazing, compromising their persistence in the sward; the timing of biomass removals also can have a significant impact on how different species are affected (e.g. inhibiting flowering or reducing the accumulation of reserves). These examples give an idea of the number of processes and factors that can be important when describing multi-species swards, and their relative importance will vary depending on the type of plants and the management system. The challenge of modelling these processes and interactions may explain the sparsity of models that tackle such systems.

The objective of this work was to use plant models for chicory, plantain, ryegrass and white clover to simulate biomass accumulation in APSIM under rotational harvest contrasting monocultures and multi-species swards. Sensitivity analysis is used to examine the model's capacity to describe the effects of major environmental and management factors (soil, climate, irrigation, and fertiliser levels) on the relative plant performance in mixed swards. We discuss how the model can be used to investigate approaches to overcome some of the challenges to simulate multi-species pastoral systems, highlighting some of the strengths and proposing developments that could enhance the model's performance and overall value as a tool in this area.

Keywords: *Biophysical modelling, plant competition, farming system, yield*

Extension of WetUp dripper wetting pattern estimation to solute fronts

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Abstract: The WetUp software was developed to approximate the position of the wetting front using an analytical solution of flow from a point source. This can be extended to approximate the position of both passive and adsorbed wetting fronts. This is achieved by altering the calculation of the dimensionless time constant. This extension was eluded to by Philip in his original paper but never taken any further. Here the extension will be explicitly given below for solutes. This will allow the WetUp method to be extended to estimate wetting front patterns for solutes.

For a surface dripper the wetting and solute front in dimensionless form for radial (R) and downward vertical (Z_+) can be approximated using:

$$\begin{aligned} T &= 2e^{R}\left(1 - R + R^2/2\right) - 2 \\ T &= Z_+^2/2 - Z_+ + \ln\left(1 + Z_+\right) \end{aligned} \tag{1}$$

and for a buried dripper the upward (Z_-), downward vertical and radial front positions are given by:

$$\begin{aligned} T &= \left[\exp(2Z_-).\left(1 - 2Z_- + 2Z_-^2\right) - 1\right]/2 \\ T &= \frac{Z_+^2 - Z_+}{2} + \frac{\ln(1 + 2Z_+)}{4} \\ T &= e^{R}\left[R^2 - R + \frac{1}{2}\left(1 - R - \ln(2)\right).\ln(2e^{R} - 1) + L(2e^{R})/2 - \pi^2/24\right] \end{aligned} \tag{2}$$

where $R = \alpha r/2$, $Z_+ = \alpha z_+/2$, $Z_- = \alpha z_-/2$, r, z+ and z- are the dimensional distances (m) and α is the reciprocal of the macroscopic length scale (m^{-1}). The dimensionless time (T) is $T = \alpha^3 qt/(16\pi x)$, where q is the flow rate ($m^3\ s^{-1}$), t is time (s), and for water: x is the water content (θ) change behind the wetting front ($\Delta\theta = \theta_a - \theta_i$) with θ_a the average θ behind the wetting front and θ_i the initial θ; for passive solutes x is θ_a; and for retarded solutes x is $R_d\theta_a$ with R_d the retardation factor. This means that the fronts reduce in distance from the source as we move from water to passive solutes and to retarded solutes. Note that for the radial flow for the buried dripper the $L(2e^R)/2$ term has a positive sign in front of it. This corrects a mistake in earlier work.

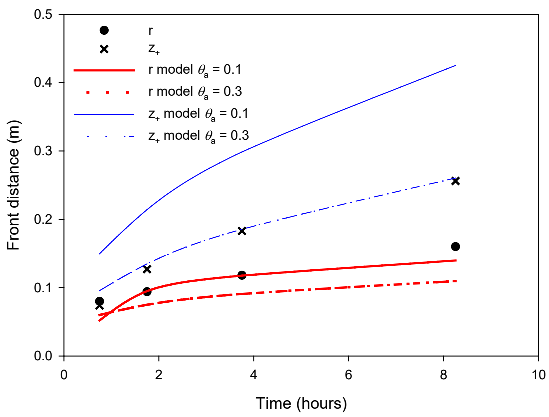

Figure 1. Comparison of measured bromide solute transport (Clothier, Soil Sci. Soc. Am J., 20,1848-1852, 1984) with model using θ_a of 0.1 and 0.3.

The model was able to adequately describe the wetting front for a passive solute compared to measured values (Fig. 1) but I could not find published data on retarded solutes to compare the model to. This extension of the WetUp model to solutes should be helpful in the design of dripper systems where the solute transport as well as the water needs to be known.

Keywords: *Drip irrigation, wetting fronts, solute fronts*

Simulations + source code = documentation

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Abstract: Writing good model documentation is time consuming and if the model is under active development, as most research models are, it can be largely out-of-date by the time it is written. When the model is one of many models in a framework and there are insufficient resources to develop the models, let alone document them, writing documentation becomes an impossibility and the lack of documentation makes further development and improvement more costly – it becomes a negative reinforming feedback loop. Faced with these challenges, we have developed an innovative, model auto-documentation, solution.

The Agricultural Production Systems Simulator (APSIM) is a farming systems simulation framework made up of hundreds of small generic functions that can be connected to larger process classes to construct models for plants, animals and soils. These models can then be combined to form simulations of a wide range of land uses. The selection and parameterisation of low-level functions, and their connection to process classes to form models which are then combined to create an on-farm land use, is all done within a single, hierarchical, APSIM input file. This text input file can be manipulated visually through a user interface so that model developers can create their models in a graphical way rather than in code. Users then use these models to create simulations using the same input file.

Having the structure of a model or simulation in a single, editable, simulation file has several advantages. It allows scientists to build new models by restructuring and parameterising existing models without having to write source code. Another advantage is that the simulation file contains enough information to automatically create a PDF document. The APSIM development team have created a tool that iterates through all elements of the simulation file. For each element, it uses reflection to extract comments from the C#.NET source code for the element's class and writes a block of text to a PDF. To demonstrate this, Figure 1a shows a wheat simulation file loaded in the user interface with the wheat/phenology/thermal time function selected. The parameterisation of this function is on the right-hand side of Figure 1a. Figure 1b shows an excerpt from the wheat PDF file at the point where the thermal time function and the following daily vernalisation function are documented. This tool has been used to document models and to create tutorials for new users that explain how various features of APSIM work. To view the APSIM auto-generated documentation visit: https://apsimnextgeneration.netlify.com/modeldocumentation/.

a) b)

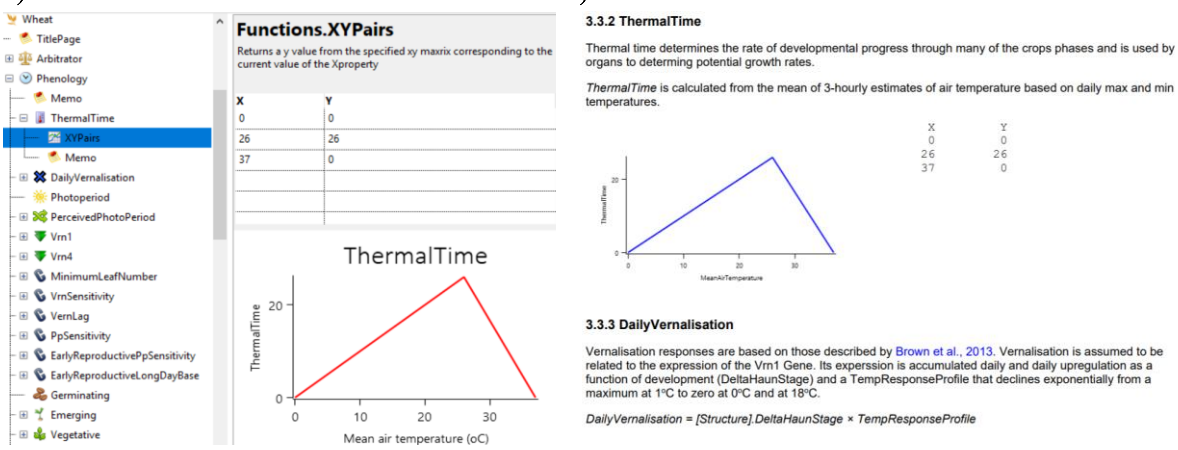

Figure 1. a) The thermal time function for the wheat model is selected in the user interface. b) This excerpt from the wheat PDF document shows the automatically generated thermal time documentation.

Keywords: *Auto-documentation, simulation documentation, model documentation*

Is it working? Conceptual testing in Integrated Modelling

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Abstract: Environmental issues typically represent an intersection of interactions among a variety of biophysical and social (human) systems. Consideration of potential management actions to resolve these issues thus requires a holistic analysis of the systems involved, such as through an Integrated Assessment approach. Towards this aim, Integrated Environmental Models have been developed to inform policy and management decisions. These integrated models typically consist of a collection of component models representing a cross-section of the systems of interest, across climatic, hydrological, and socio-environmental contexts. This paper describes a conceptual testing approach to identify issues with model behaviour and alert issues of conceptual disconnect between models and modellers.

The presented approach represents lessons learnt in the development of an Integrated Environmental Model for the Lower Campaspe catchment (Victoria, Australia). Early and constant model integration attempts are prescribed and leveraged as a vehicle for communication between modellers and, where possible, stakeholders. The principle aim is to identify broad high-level conditions which indicate incorrect or unacceptable model behaviour that point to errors in the modelling or else alert one to potential disconnect within and across the modelling process. Because integrated modelling is inherently a human-driven process, available tooling should not be valued more highly than the people involved. The approach therefore flexibly incorporates software testing practices (technical expertise), diagnostic sensitivity analysis (modelling expertise), and leverage qualitative knowledge (domain expertise) in test design. Conceptual testing is expected to be useful in cases where software development practices and tooling may be regarded as a secondary concern to the production of science; where the use of unit or functional tests are not promoted or their adoption otherwise infeasible. While programmatic tests are preferred due to their ease of repeatability and comparably low cost, qualitative assessments should still be leveraged if necessary, and a workflow designed so that relevant experts may assess results.

To develop conceptual tests, it is suggested that modellers identify and describe (high-level) conditions which influence model behaviour (of both component models and integrated) and their expected outputs, or otherwise describe (qualitative) bounds, exceedance of which indicates poor model behaviour. As part of the modelling process, development of conceptual tests can aid in raising modeller awareness of the context in which one domain fits in with the overarching modelling objective and facilitates early recognition of the flow of impact. Change in one model due to a shift in goals or stakeholder feedback may necessitate changes in other aspects of the modelling. Communication and awareness are therefore key to resolving disconnect within the modelling process. Without sufficiently addressing disconnect, model development including testing and validation can quickly become an error-prone time sink.

Examples of tests include expected dam level response after prolonged drought or rainfall (hydrological behaviour), the corresponding water allocations (policy behaviour), and farmer decisions under such conditions (agricultural/social behaviour). These conceptual checks are then implemented which can alert one to unexpected results, which may be due to a mismatch between model formulations, error in coupling, or other issues in the modelling. Such tests may lead to the recognition that unsuitable metrics are relied on to communicate results, insufficient data is available, the (spatial/temporal) scale requires adjustment or that available computational infrastructure is insufficient. Examples from the Lower Campaspe case study are provided herein.

Keywords: *Integrated Modelling, integrated testing, testing workflow*

Dynamic simulation of crop rotations to evaluate the impact of different nitrogen management strategies on water quality in Southland, New Zealand

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Abstract: Nitrogen lost from agricultural fields is one of the main causes of water pollution. In New Zealand, the National Policy Statement for Fresh Water Management authorises Regional councils to administer limits around the amount of nitrogen discharged into water systems. Enforcement of this policy requires reliable ways to quantify nitrogen losses from land uses in catchments and test future land use options for minimising those losses while maintaining farm profitability. Since measurement of nitrogen loss under field conditions can be technically challenging and costly, simulation models have often been relied on to provide this information.

The evaluation of environmental impacts from agricultural activities at a catchment scale requires integration of modelling tools designed to work at different levels. A dynamic farm systems model is needed in this context, to capture the impacts of land use changes and management decisions on water and nitrogen fluxes in the soil-plant interface. Generated information from this level can then be scaled up by hydrological models to determine the impact of farming activities at the catchment and regional scales. In this work, we used the **A**gricultural **P**roduction **S**ystems s**IM**ulator (APSIM), a process-based farm systems model, to evaluate the effect of fertiliser nitrogen management on crop production and nitrogen leaching from cropping rotations in the Southland region of New Zealand. For this, we developed a general simulation that can be modified with relatively simple inputs to describe a variety of farming systems typical of the region. We test and demonstrate this abstraction using simulations of three rotations (continuous wheat, pasture-wheat-grain oats, and wheat-green oats-fodder beet-peas, hereafter, Rotation 1, Rotation 2 and Rotation 3, respectively) modelled for 35 years (1980–2015). Two fertiliser management options were evaluated for each crop rotation: scheduled management where fertiliser nitrogen rates and timing of application used a prescribed schedule, and soil-test management where fertiliser nitrogen rates and timing were based on the analysis of simulated soil nitrogen levels within a specified time period.

Results indicated APSIM-estimated crop yields were within yield range for the region, and nitrogen fertiliser management had a negligible effect on crop yield. The estimated average nitrogen fertiliser applied to crops under the soil-test management was either similar or lower (by 11–12%) than nitrogen fertiliser applied under the scheduled management. The soil test management also resulted in similar or lower (17–32%) nitrogen leaching than the scheduled management (Fig. 1). These results fundamentally show that soil-test based fertiliser application has the potential to increase fertiliser nitrogen use efficiency and reduce the risk of nitrogen loss to the Southland catchment water systems. These results also demonstrate the capability of our APSIM setup to produce realistic crop production levels and account for intra- and inter-season variability in soil nitrogen and weather conditions. Using such simulation setup is a promising tool to generate valuable data to assist in assessing the productivity and environmental effects of cropping systems and alternative management options for nitrogen mitigation to improve water quality.

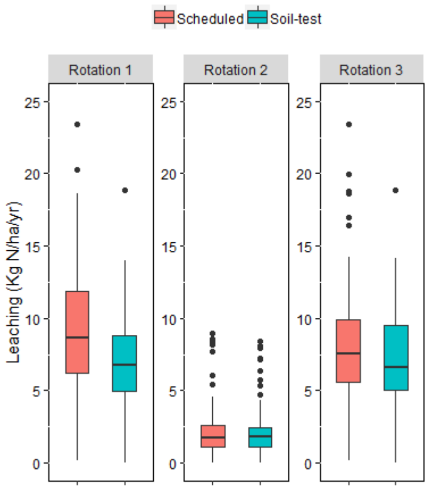

Figure 1. APSIM-estimated nitrogen leaching for two fertiliser management and three crop rotations.

Keywords: *Integrated modelling, nitrogen management, water quality*

Developing the Crop Livestock Enterprise Model (CLEM) – a whole-farm bio-economic simulation model

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Abstract: Farms vary widely in nature, from small family subsistence farms to extensive beef or cropping farm businesses. Regardless of farm size, biophysical processes interact with potentially limited resources following dynamic management rules and decisions. The complexities of these interactions make it difficult to predict outcomes resulting from changes in management and/or environmental conditions. Farm simulation models are a valuable tool to explore the outcomes of different management practices on farming systems. Modelling a whole-farm is by necessity a multi-domain task where users within a given expertise often use the model to observe outcomes across the whole-farm. Often a lack of sophisticated modelling technique on behalf of uses can result in challenges in providing a user-friendly environment in which to design the range of complex farming simulations. The Crop Livestock Enterprise Model (CLEM) was developed as a component-based farm simulation model, capable of simulating a wide range of farming systems over the short to medium term (20 years). It is based on the spreadsheet-style Integrated Assessment Tool (IAT) and Northern Australia Beef Systems Analyser (NABSA) models, which have been successfully used in subsistence smallholder crop-livestock systems in developing countries and in large beef cattle production agribusinesses in northern Australia, respectively. The Crop Livestock Enterprise Model builds upon the fundamentals of these precursor models whereby all resources on a farm are tracked as they are used by or created from a range of farm activities (Figure 1) and allows for constrained resources such as finances and labour to influence the outcome of the farming system simulation and to examine the limitations of these systems. This model has been consciously designed to be flexible and easy to use for researchers with a range of modelling skills and is and is now released within the Agricultural Production Systems sIMulator (APSIM, Next Generation).

The model offers the following features:

- a graphical, tree-based structure is built to represent the farm by adding the required components
- output, in the form of ledgers of all resources in and out of the system, facilitates detailed analysis.
- an individual-based ruminant energy and growth model is included
- crop and pasture production data are provided from other models, field data, or expert opinion
- stochastic processes are available, allowing users to investigate risk and rare events over multiple runs of a simulation

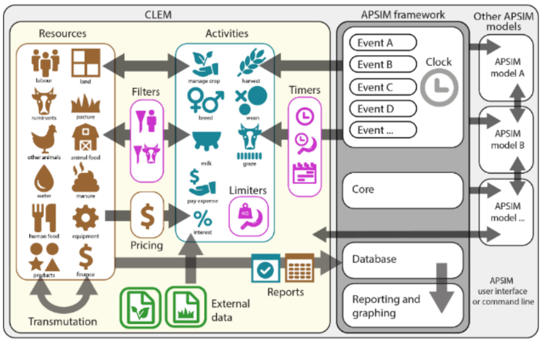

Figure 1. Conceptual diagram of the Crop Livestock Enterprise Model (CLEM) operating within the APSIM Next Generation simulator. The resources and activities shown represent a subset of those that may be required.

Keywords: *APSIM next generation framework, bio-economic model*

EXTENDED ABSTRACT ONLY

Integrative modelling of phosphorus losses from crop production

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Abstract: Fertilization, crop uptake followed by plant harvest, runoff and erosion, and transformations of phosphorus (P) in soil are the major factors influencing the P balance of croplands. Spatially explicit assessment of global P losses from croplands and identification of regions and crop types with inappropriate P fertilization are essential to support police makings for improving the efficiency of P fertilization. Here we applied a global gridded crop model PEPIC to estimate global P losses for the period of 1998–2002 with a 0.5-degree spatial resolution associated with the cultivation of maize, rice, and wheat. It explicitly accounts for the interactions between fertilization, crop uptake and harvest, runoff and erosion, and soil P transformations. The simulated P losses to the environment (outside crop fields) for each grid include P losses from surface runoff and leaching, and soil erosion. The harvested fraction of P in yields and residues removed from fields is not defined as a loss to the environments since it enters the food chain. P removed by residues returned to the field is not a loss, but rather a recycling flux.

According to the simulation results with actual P-fertilizers applications during 1998–2002, global P losses into the environment from leaching and erosion totalled 409, 429, and 392 Gg P yr^{-1} (Gg = 109 g) for maize, rice, and wheat, respectively, accounting for 15, 11, and 9% of the respective P inputs (P_{in}) (Table 1). Maize had the highest P recovery rate in yields (with a ratio of P_y/P_{in} of 0.72), followed by wheat (0.48), while rice had the lowest value (0.26) (Table 1). The major results show that soil erosion contributes about half of P losses; crop residue takes a large amount of P away; China and India are hotspots of P losses. Globally, about 2/5 of P losses can be avoided without significant compromising crop yields.

The spatially concentrated P losses to the environment found in this study provide an option to mitigate the environmental problems caused by P losses from agricultural areas through more evenly distributing P fertilizer application, i.e., redistribute P inputs from overuse regions to regions showing a deficit. Due to the different concentration patterns among the three crops and across regions, it is important to identify crop-specific P fertilization conditions. In this study, crop management practices, e.g. P fertilizer inputs, fraction of irrigated areas to total cultivation areas in each grid cell, and crop growing conditions, as well as growing season precipitation, are responsible for the differences among the three crops. The different management approaches and climatic conditions further highlight the significance of crop-specific assessment.

Table 1. Comparison of phosphorus (P) inputs (P_{in}), P losses to total environment (P_{tot}), P losses with soil erosion (P_{ero}), and crop production among the baseline, optimal (optP) and optimal with conservation (optP-con, i.e., keep 75% residue in field and reduce 50% of erosion) scenarios

Maize				Rice			Wheat		
Variables	baseline	optP	optP-con	baseline	optP	optP-con	baseline	optP	optP-con
P_{in} (Gg P yr^{-1})	2795.12	1849.43	1442.73	3761.1	674.5	354.68	4293.79	1296.97	1002.3
P_{tot} (Gg P yr^{-1})	409.23	293.07	240.01	429.04	240.69	248.2	391.92	191.69	155.38
P_{ero} (Gg P yr^{-1})	261.84	220.99	160.61	83.45	52.58	47.92	194.81	126.84	86.7
Production (Tg yr^{-1})	808.72	812.24	824.25	740.46	740.65	743.9	584.9	585.27	593.85

Keywords: *Phosphorus losses, integrative assessment, global modelling, mitigation, PEPIC*

Integrated software system with 3D imaging to assess cattle and assist in meeting market specifications

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Abstract: Real-time assessments of cattle using off-the-shelf Red Green Blue-Depth (**RGB-D**) structured light cameras integrated with decision support tools such as the BeefSpecs drafting tool have the potential to assist producers manage risks associated with meeting carcass market specifications [P8 fat (mm) and hot carcass weight (kg)]. In addition assessing muscle score will lead to the prediction of denuded lean meat yield.

Data requirements to develop an integrated software system with 3D imaging include:

- Objective or subjective assessments by trained technicians of:
  - Hip height (cm),
  - Ultrasound P8 fat (mm), and
  - Muscle score. and
- Final view of alignment
  - Multiple 3D images of beef cattle taken from the shoulder to the tail head covering the pin bones and stifle region.

Individual point cloud representations, using a pinhole camera model, convert the final view of alignment from several RGB-D cameras. A compact feature vector computes and encodes the surface curvature for each element of the point cloud. Supervised learning then uses the feature vector to develop the relationship between the 3D images and the assessed traits (i.e., P8 fat and muscle score).

These traits with radio-frequency identification (RFID) and weight of individual animals integrate with the BeefSpecs tools (e.g., BeefSpecs drafting tool and BeefSpecs Calculator iPhone/Android app). The integration of 3D cameras and BeefSpecs is potentially worth well over $51M pa to the beef industry. This integrated software will result in on-farm practice change for improved animal productivity and profitability (e.g., more efficient use of feed due to better management decisions and selecting for higher yielding cattle).

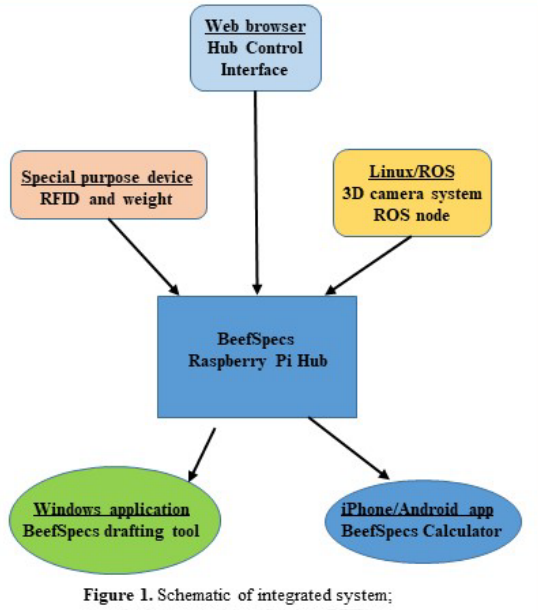

Figure 1. Schematic of integrated system; radio-frequency identification (RFID); Robot Operating System (ROS)

The objectives of this study are to report on the development of:

1. Calibration procedure,
2. Continuous optimization framework for depth-sensor viewpoint selection to determine the optimal angle of view and camera positioning,
3. Adequate 3D model for capture and practicality of animal stance for deployment in the field,
4. Online symmetry detection to determine when neutral posture is reached for assessing P8 fat and muscle score, and
5. Evaluation of an integrated software system with 3D imaging to assess cattle and assist producers in meeting market specifications.

Keywords: *BeefSpecs, Red Green Blue-Depth (RGB-D), feature vector, supervised machine learning*

A multi-sensor approach to reduce data uncertainty in development of cattle behaviour classification platform for reliable prediction of animal state

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Abstract: Increasingly, data collected with on-animal sensors in combination with analytics platforms are being used to support complex animal management decisions (e.g. cow collar sensor for heat detection). Global Navigation Satellite System (GNSS) devices, providing frequent high accuracy measurements, are becoming more common as research tools. They can be used to determine animal location and behavioural state. However, GNSS positional errors affect the accuracy of both animal location and determination of behavioural state. Consequently, estimates of distance travelled by animal would be inflated and effects will be more pronounced with increasing frequency of measurement. Uncertainty of GNSS measurements translates into less certain identification of activities such as walking, lying or standing, decreases the value of the data as an input for farm systems modelling, and increases risk in decision support system models.

In this study, a GNSS animal tracking solution was developed to determine animal location and behavioural state. A number of published articles highlight different methods of GNSS data pre-processing, including development of models where visual observation of animals are used for calibration of positional data against activity. Initially, we approximated distance travelled after pre-processing of data using published algorithms. We then explored improvement of existing methodologies by using additional attributes such as HoBo (pedometer) data. First field trials showed that observational data was necessary for evaluation and refinement of newly developed algorithms and measurement of uncertainty for distance travelled and animal activity states. Therefore, the aim of our next study was to establish a detailed study to validate GNSS accuracy and precision through aerial imagary in both static and dynamic scenarios.

During the trial dairy cattle were equipped with RTK GNSS collars. Inertial Measurement Units (IMUs) placed on animals' necks and legs were used as an additional data source to aid data cleaning and to improve the range of identifiable behavoiural states. Video recording of the trial was conducted using 4 cameras. Noise and outliers in the GNSS positional data occurred due to atmospheric effects, signal multipath through objects in the environment, and operational conditions of the collar such as significant antenna tilt. Non-processed data affected estimates of distance travelled by animals as well as definition of behavioural states. Two-stage data pre-processing was applied to correct outliers and noise in GNSS positional data by combining it with HoBo data to accurately differentiate between lying and standing. As a result, GNSS positional accuracy significantly increased while estimates of distance travelled by animals decreased up to 43%. Animal head state parameters such as 'Head up' and 'Head down' were obtained from the neck IMU, verified by the video observation. A decision tree was developed to transform specific combinations of features into animal states. Results from decision tree processing were verified against manually classified animal state data obtained from video frames. Accuracy assessment has shown that 'Grazing' and 'Rumination while lying' states were classified with high accuracy, 91.7% for Grazing and 93.9% for Rumination while lying. 'Rumination while standing' and 'Sleep' were classified with 79% and 76.1% as well. No instances of 'Walking' and 'Drinking' states were classified correctly. Further improvements of the GNSS hardware positional accuracy and the frequency of IMU-derived animal leg movement data is necessary to correctly classify 'Walking' and 'Drinking' states. Use of a combination of sensors compared with GNSS data alone improves positional accuracy and behaviour classification, reduces uncertainty in distance measurements and broadens application areas for the outputs as they might be used in farm systems modelling as a reliable source of data.

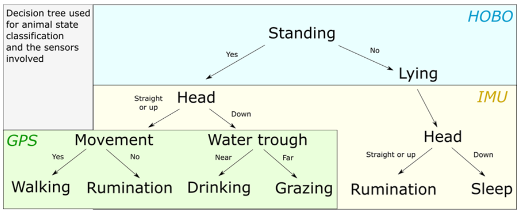

Figure 1. Decision tree to predict animal state.

Keywords: *GNSS, IMU, animal behaviour classification, pastoral farming, farm systems modelling*

Transforming climate research into useful information: A future climate atlas for the Australian wine industry

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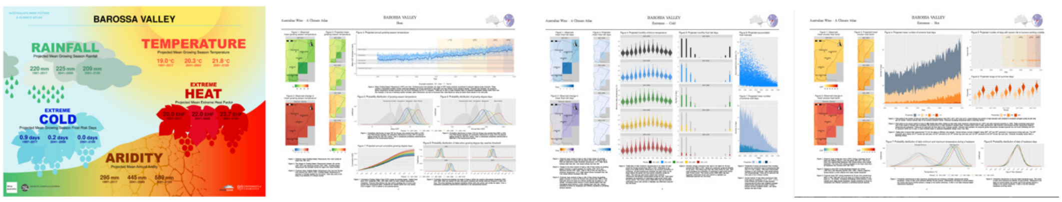
Abstract: Fine-scaled climate information tailored for particular industries is vital for making good management decisions now and into the future. The Climate Futures team works with a range of industries and land managers (e.g. hydroelectricity generators, agriculture and conservation, emergency and fire managers) to make management decisions necessary to plan for a changing climate. By incorporating the high frequency and seasonal information available in regional climate projections they are better able to consider the impact of climate variability and long-term climate change. One example of our recent work is the online atlas of climate information for all Australian wine regions, providing information to grape growers and wine makers about climate trends for the near, mid and long-term horizons. The atlas showcases the most up-to-date climate information at the finest resolution available in Australia.

Future trends in mean climate conditions, variability and extremes are visualised with reference to the current and historical climate. High resolution maps and time series for each region are presented to show the projected change in climate indices over time, highlighting the variability within and across the wine regions of Australia.

For every wine region across Australia (71 in total), viticultural indices are presented that describe temperature, heat accumulation, heatwaves, rainfall and moisture. These were selected following intensive industry engagement spanning regions, commercial scales and styles. These were calculated from the climate simulations collaboratively generated by the CSIRO and the University of Tasmania Climate Futures Team, which have a range of domains of varying temporal and spatial resolutions 5km^2 to 50km^2. These simulations are from CSIRO's Conformal Cubic Atmospheric Model (CCAM), dynamically downscaling six host global climate models (GCMs) from the Coupled Model Intercomparison Project (version 5), resulting in a six-member ensemble of high-resolution climate simulations. Each host GCM followed the Representative Concentration Pathway 8.5 watts per square meter scenario.

This study has developed a future climate atlas for the Australian wine industry. The new atlas will help to answer the question – What will my region's climate look like in the future? This is essential knowledge for making good management decisions and supporting strategic decisions over the longer term such as changing varieties or vineyard sites both within and between regions. Such knowledge will help the wine industry understand how climate change could affect grape yield, profitability and wine quality across Australia into the future. This presentation will report on the process we used to translate the climate simulations into a useful, usable, accessible final product.



Keywords: *Climate modelling, data visualisation, research translation, industry engagement*

Can farmers that irrigate assist in the management of summer-time peak electricity demand? A preliminary study from Mid-Canterbury, New Zealand

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Abstract: Electricity network managers seek to avoid the occurrence of high peak electricity demands because they accelerate wear on infrastructure, can load infrastructure beyond prudent levels, can trigger need for expensive new investments, increase energy losses in transmission, and may result in higher network charges. Managers have several techniques for managing peaks including: starting up generation, shedding load through ripple control of hot water cylinders and through agreements with industrial users, and time-of-use charging for some electricity users. The Mid-Canterbury district of New Zealand faces an atypical pattern of electricity demand with peaks in summer at more than three times that of winter. About 70% of the electricity usage in summer in this district is from irrigation activities. We sought to find out to what extent farmers could assist with managing the summer-time peak demands through strategically reducing their hours of active irrigation during different management windows during summer.

We used the simulation model APSIM set up for pastures irrigated with centre-pivot systems with 200 kg N /ha urea fertiliser. The maximum allocation of irrigation was 3.5 mm /day from September to April, but water was only applied when justified by the soil water deficit. We simulated 45 years of pasture growth in five soils and a grid of nine locations covering the range of the district's soils and climates. A fully-irrigated system was run as a control and then a series of management options of increasing hours of no irrigation and varying windows of management. Outside these management windows, irrigation could be used 24 hours a day. Irrigation during weekends was not restricted.

Results for one soil and location are shown in Figure 1. All management windows and hours of restriction reduced pasture production, but the effect reduced as the window narrowed and the management hours decreased. Combined with electricity usage data, which shows some capacity to shift timing within the day, this preliminary work shows that there is some potential that irrigation can assist with managing electricity peak demands in summer but, in most locations and soils, this will come at a cost of reduced production. Restricting irrigation only during forecast peaks may be more attractive. This work is part of a larger programme to assist in the design of new electricity tariffs and includes in-depth workshops with local farmers to better understand their needs and restrictions. It will also contribute to the design of farmer agents in a multi-agent simulation model.

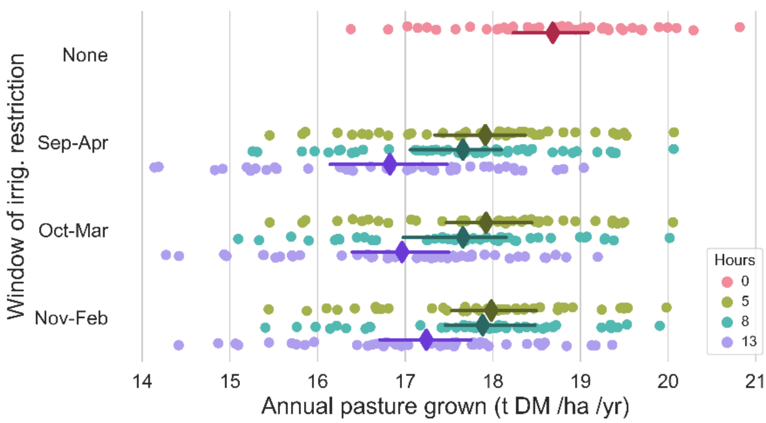

Figure 1. Effect of irrigation restriction on pasture production in the warmest/driest location and a soil with 50 mm of plant-available water.

Keywords: *Irrigation, peak electricity demand, pasture growth, water balance*

Pasture API: A digital platform to support grazing management for southern Australia

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Abstract: Extensive ruminant livestock production is complex, and it is difficult and time-consuming to obtain quantitative information for decision making (e.g. biomass and quality of forage). Increasingly data from historic records, seasonal forecasts, or near real-time data from remote or on-farm sensors. However, there is limited capacity to compile, integrate and analyse these data. In some cases, there are decision support tools available with such analytical capability, but the time required to learn and apply these to gain the benefits is significant, and a major disincentive to their widespread adoption. Based on the need for simple, entry level, decision support for the livestock industry we have developed the Pasture API (Application Programming Interface) platform. The aim of the Pasture API was to build a seasonal pasture forecast system that can provide a forecast to specific locations up to 6 months into the future for anywhere in Australia and made available to a variety of client software packages. The platform is able to forecast a wide range of simulated data outputs including pasture biomass, ground cover, supplementary feeding and livestock growth.

The Pasture API application required the integration of a number of both new and existing analytical capabilities, which are summarised below and described in more detail in this paper.

1) **Ruminant grazing simulation engine**: The GrazPlan biophysical pasture and ruminant nutrition model (adapted from GrassGro™ software) was repurposed for use as the modelling engine in a back-end service infrastructure.
2) **Flexible tactical grazing scenarios:** The GrazPlan models were incorporated into a new software application for batch processing of tactical grazing scenarios. This application was called GGTactical.
3) **Dynamic platform for connecting the pasture simulation engine with data streams:** We used CSIRO's Senaps platform to connect the GGTactical application with a range of spatiotemporal data streams so that simulation scenario workflows could be implemented.
4) **Demonstration interface:** A demonstration website (Pasture Tracker) was built to interact with the Pasture API application and implement workflow's based on location and livestock enterprise details. Currently the software is hosted internally by CSIRO, with the intention that a version become publicly available in the near future.

We demonstrated that Pasture API is able to replicate simulation of a livestock grazing scenario, as can be done with more complex modelling software, such as GrassGro™. Key production metrics such as net primary productivity (NPP) of pasture, supplementary feeding, ground cover and liveweight of stock were charted. These were reported both as historic percentile values across a season, the now-cast (current) value, and a probabilistic forecast for a predefined period of time (e.g. 3 or 6 months).

To compare the effects on forecasts for various input data streams that were available, a sensitivity analyses was conducted. This provided information about the suitability of more generic data streams (e.g. national soils database) for forecasting, comparing forecast outcomes for those where local data were available.

The Pasture API project demonstrates the ability to create easy to use, yet powerful, decision support systems for the livestock industry. This is a novel integrating technology that we expect to continue to develop to make use of the many sources of sensor and archive data that are collected within livestock businesses. This information is expected to increase the precision across a range of interventions, including; stocking density, timing of paddock rotations, and supplementary feeding. In the future we expect to increase the use of local data streams and refine the data delivery processes to produce the site-specific information sought by the industry for decision making.

Keywords: *Simulation modelling, ruminant nutrition, extensive grazing systems, Senaps*

Modelling feedlots using the MEDLI model framework

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Abstract: Model for Effluent Disposal using Land Irrigation (MEDLI) is a biophysically-based daily time-step model released in 1996 to facilitate designing effluent irrigation schemes. The model simulates a waste stream generator producing effluent that is treated in a pond system with a wet weather storage pond from which the effluent is irrigated as required to an area of land growing vegetation (Gardner et al. 1996). To complement the existing waste stream generator options, MEDLI is undergoing further development to include rainfall-dependent waste streams, including that generated by rainfall wash-off from feedlot production pens. This will facilitate MEDLI's use for designing effluent irrigation schemes associated with feedlots.

The feedlot pen model attempts to model the complex dynamic processes within feedlot production pens that impact on the quantity and quality of runoff using a daily time-step mass balance approach. An early description of the feedlot model for MEDLI, focusing on runoff quantity, was provided by Atzeni et al. (2001). Since then, the hydrology component has been substantially improved to generate daily surface and sub-surface pad moisture output for use in predicting odour emissions (Atzeni et al. 2015), as well as runoff quantity and quality. In this paper, we present the modelling approach and model algorithms used to simulate the waste stream from the feedlot production pens. Supporting references are detailed in Atzeni et al. (2015).

The MEDLI feedlot pen model is designed to simulate a modern feedlot yard with equal-sized production pens having adequate slope, and operating within the recommended Australian guidelines. Cattle can be designated to up to four markets, with market-specific entry and exit weights, daily weight gain, proportion of total herd designated, and proportion of pens occupied. Daily calculations are performed on a pen by pen basis, to model the key processes of herd dynamics, manure (faeces+urine) production, assimilation of the fresh manure into the pad, pen hydrology and pen cleaning. Herd dynamics include modelling animal mortality and pen stocking. When animals in a pen reach the exit weight for their market type, the model flags that the pen is vacant and drafts another mob (of the same market type) into another vacant pen if possible, or else the same pen. Manure production relies on BEEFBAL (QPIF 2004) or similar model to provide the market-specific annual manure production (total solids, volatile solids, total nitrogen, total phosphorus, salts and water) of each animal which is then used to determine the solids, nutrient, salt and water loading onto the manure pad. Assimilation of the fresh manure into the pad uses a two-layer model for the manure pad, assuming no loss of water or solids below the lower layer of the pad. The two layers capture the dynamics of pad hydrology and composition, including the impacts of rainfall, evaporation, animal stocking, manure accumulation, volatile solids decay, pen cleaning, runoff and manure erosion during runoff. Pens are cleaned at intervals to remove the excess manure, and involve considering the specified minimum number of days since a pen is cleaned, the pen's pad moisture content, pad depth, and the number of pens being cleaned each day. By modelling these processes, the fate of the nutrients, salts and solids from the manure pads is simulated as shown in Figure 1.

Validation of the feedlot pen model hydrology was undertaken using four field-collected data sets from three South East Queensland feedlots. The prediction of runoff quantity appears closely correlated with measured data. However, the runoff quality predictions require calibration of the total nitrogen, total phosphorus, and salt runoff concentrations with actual or expected holding pond chemistry. Data collection is in progress to allow further testing and validation of the feedlot pen module.

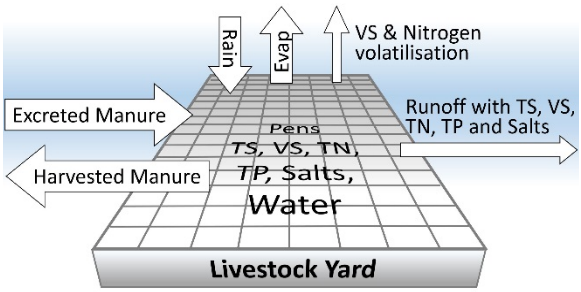

Figure 1. Key processes modelled to describe the movement of total solids (TS), volatile solids (VS), total nitrogen (TN), total phosphorus (TP), salts and water in feedlot production pens.

Keywords: *MEDLI, model for effluent disposal using land irrigation, feedlot pad runoff modelling*

Optimal flowering period and corresponding sowing window shifting with Genotypes and climates in Australia Northern Grains Region

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Abstract: Australia, as one of major wheat exporters, greatly influences the global wheat market and has an important contribution to global food security. Rainfed cropping is the major land-use in the Northern Grains Region of Australia (NGR), encompassing Queensland and New South Wales. Wheat (Triticum aestivum) is sown typically in autumn (April- early June) and harvested in spring (Late September-early December) in this region. Water stress, frost damage in reproductive stage and heat stress during grain-filling are greatly limited the wheat production in this region. Research showed that, at a given environment, there was a period, when wheat flowered at, having the minimum effects of extreme climate events (e.g. drought, frost and heat stress occurred during sensitive stage) on crop yield. This was defined as the optimal flowering period (OFP), which is determined by stresses including water deficit (drought), extreme high (heat) and low (frost) temperatures occurred from just prior to flowering to reproductive stages after flowering. Therefore, it is important to identify the OFP at a given environment for gain the maximum grain yield by the manipulating the phenological development via agronomic management (sowing time) and variety selection.

Here, a simulation analysis was conducted at 12 representative sites cross the wheatbelt of NGR to identify the changes in the OFPs and corresponding sowing windows in response to genotypes by accounting for the effects of frost, heat and water stress on wheat yield. Two years' experiments were conducted at 12 sites with four contrasted varieties (fast spring, slow spring, fast winter and strong winter) and time of sowing. The data collected from the experiments were used to optimize the parameters of wheat module in the Agricultural Production Systems sIMulator (APSIM). With the optimised parameters, we simulated wheat grain yield and flowering dates across the locations with historical climatic records (1961-2018) for defining the OFP and corresponding sowing window (to achieve the OFP) for each variety in each location. Simulated crops were sown at weekly intervals from 10th March to 28th July of each year. OFPs were defined as the flowering period which was associated with a mean yield of ≥95% of maximum yield from the combinations of 68 seasons and 21 sowing dates. The optimal sowing window (OSW) was regarded as the period that achieved the OFP for each variety and site.

The simulation results showed a clear shifting trend of the OFP and OSW from the cold and dry environment and from fast spring variety to strong winter variety. From cold and dry environment to warm and wet environment, the start of OFP for fast spring variety shifts from early August to late September. Generally, the durations of OFPs were narrowed down from fast spring to strong winter varieties, and the start and end of OFPs were pushed forward about 4-20 days across sites. Correspondingly, to achieve the OFP, the start of OSW for fast spring variety was shifting from mid-April to early May from the cold and dry environment to the warm and wet environment. The start of OSW were pushed backward about 20-30 days from fast spring to strong winter varieties. This affirms that it is essential to choose the right varieties and sow it in the right time according to local environment to maximise the grain yield.

Keywords: *Optimal flowering period, optimal sowing window, APSIM, Northern grains region*

EXTENDED ABSTRACT ONLY

Background emissions of nitrous oxide N_2O by global forest and grassland soils

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Abstract: Atmospheric N_2O concentration has been growing for decades, yet large uncertainty remains in terms of the magnitude and controlling factors of N_2O emission. In this study, we collected background N_2O emission fluxes, soil properties, vegetation type, and climate variables of forest and grassland in situ observations from almost 200 published literatures. A total of 357 datasets for forest at 161 sites from 32 countries, and 203 datasets for grassland at 81 sites from 25 countries were finally selected. Here, linear mixed model (LMM) was used to evaluate the factor that correlated with annual emission flux of N_2O. Study site was included as a random factor to avoid the spatial autocorrelation that introduced by clustering replicates. The fixed factors involved in LMM analysis included both continuous variables such as annual mean temperature (°C) and precipitation (mm), edaphic physicochemical properties, and atmospheric nitrogen deposition (N_{input}, kg N ha^{-1} yr^{-1}), and classification variables such as soil texture (coarse, median, and fine), climate zone (cool temperate, warm temperate, and tropical), dry-wet (arid and humidity), and vegetation types (evergreen coniferous, evergreen broadleaf, evergreen mixed, and deciduous). The analysis result of LMMs shows that both soil texture and climate zone are the principal determinants of the spatial distribution of global forest and grassland annual N_2O emissions. N_2O emissions in soils with coarse texture are significantly lower than that in fine texture soils. In addition, N_2O emissions in tropical zone are remarkably higher than that in temperate zone. Moreover, vegetation type is also one of the main factors that affects the spatial distribution of global forest annual N_2O emission fluxes. For example, the highest and lowest annual N_2O emission flux are in mixed and deciduous forest by 2.506 kg N ha^{-1} yr^{-1}, 0.931 kg N ha^{-1} yr^{-1}, respectively. Dry-wet condition is another important factor that affects annual N_2O emission fluxes by global grassland. The average annual N_2O emission flux of wet region (1.009 kg N ha^{-1} yr^{-1}) is remarkably higher than that of dry region (0.350 kg N ha^{-1} yr^{-1}).

Keywords: *Forest, grassland, N_2O emission, controlling factors*

Data assimilation of APSIM wheat and soil state variables in a synthetic study framework

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Abstract: The growing demand for world food requires an increase in yield. Accurate yield prediction with an understanding of spatial and temporal variability can help farmers make key decisions on field management to achieve this increase, but current models cannot achieve the desired accuracy on their own. Remote sensing can provide high resolution information on key variables every couple of days to allow within-field spatial variability to be assessed, but these images must be merged with the physically-based crop models to gain an understanding on the future crop development. This can be achieved by utilising data assimilation technologies such as the Ensemble Kalman Filter (EnKF). Such methods successively update the state variables (e.g., leaf area index and soil moisture) in the crop models with the external observations during the evolution of the model, with a consideration of the uncertainties from both the model and observations. Several studies have demonstrated the potential of assimilating remote sensing leaf area index (LAI) and surface soil moisture content (SSM) products into crop models at regional scale, with results validated using official statistical data. However, to provide useful information for field management such predictions must be available at field scale, and so experiments must be conducted with high-resolution remote sensing images to develop and demonstrate this capability. Moreover, the most important states for model constraint such as biomass, vegetation water content, leaf and soil nitrogen must be determined by in-field destructive sampling only. Consequently, a comprehensive understanding of the impact from assimilating the range of possible crop and soil states needs to be explored for improving wheat monitoring most efficiently.

The Agricultural Production Systems sIMulator (APSIM) is a highly advanced agricultural model simulating the interactions in a plant, soil, climate and management system. This research explores the potential of assimilating external observations of all observable model state variables of APSIM with the EnKF algorithm in a synthetic study framework for the purpose of wheat monitoring and yield prediction. All prognostic state variables in APSIM have been tested, including the timing of assimilation (e.g., phenology stages) and the frequency of available observations.

The results show that the assimilation of LAI, leaf weight and nitrogen, stem weight and nitrogen, surface soil water content and soil nitrogen may lead to a better yield estimation. The yield estimation received stronger impact from data assimilation when state variables are assimilated in the phenology stages of flower and grain development than in other stages. The interval of observation availability is recommended to be at least every 12 days.

Keywords: *APSIM, data assimilation, EnKF*

Partial differential equation based modelling and simulation for long-term dynamical behaviour of two invasive species

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Abstract: Spreading and invasion of populations in space is a ubiquitous biological phenomenon. The ecological impacts of invasive species is a widespread concern and considered as a major threat to biodiversity. A great deal of research has been performed on the ecological interactions between native and invasive species. Understanding the mechanisms of ecological interactions, among the species, which influence the success of invasive species into new territory is a challenging task in mathematical modelling and the mathematical modelling of ecological invasion is an area of extensive current research.

Among a wide range of modelling approaches, agent-based modelling (also known as individual based modelling) and continuum modelling, are popular and coherent techniques for studying the complex systems in ecology. For populations beyond sizes that can be reasonably handled using an individual based model, continuum models, usually formulated via partial differential equations, are a practical alternative. In some cases continuum models have an added advantage over individual based models in that it is possible to develop general theories about the long-term behaviour of the systems modelled without performing any calculations. This talk is concerned with the long-term dynamical behaviour of two invasive species modelled by classical Lotka-Volterra competition diffusion equations, a continuum model (a partial differential equation based model), with free boundaries. We investigate the behaviour of this system in the case that one invasive species is strong, and the other weak, using two numerical methods: front tracking, and a level-set method. We found that for different choices of initial data, the long-term spreading behaviour of the species results in either co-existence of both species, or vanishing of at least one species. We identified critical parameter values (threshold points) within our parameterized initial functions, so as the parameters varied across that threshold point, the long-term dynamical behaviour of the species changed from one type to another. In the co-existence case, both the species spread, and due to the different spreading speed the species segregate with the two populations concentrating in separate moving territories. The strong species with slower spreading front concentrate in an expanding ball and the weak species with faster spreading front gather in an expanding spherical shell outside the habitats of strong species.

We also investigate the long-term dynamical behaviour of invasive species in two spatial dimensions and subsequent topological changes using level set representation of free boundaries. We show that irrespective of the initial shapes of populated regions, the boundaries of the spreading population range of the species evolve into circular moving boundaries, and later the populations propagate as circular travelling waves. Long-term dynamical phenomena of two invasive species appearing in the Lotka-Volterra competition equations with time periodically varying intrinsic growth coefficients are also studied numerically. Our simulation results also suggest that the invasion and spreading behaviour of the competitor is time-periodic.

Keywords: *Lotka-Volterra competition model, invasive species, free boundary, front tracking method, level set method*

Inferring the interaction rules governing collective movement of players in field sports

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Abstract: Moving animal groups display the capability to perform highly coordinated maneuvers without a centralized control. Familiar examples from nature that have been studied extensively include flocking behavior in birds, schooling fish and pedestrian movements. It has been demonstrated that complex patterns of collective motion can arise from simple interaction rules through simulation, and it has been hypothesized that these simple rules reflect the processes used by individuals to govern their movement and behavior. While it is unclear to what degree these simulated mechanisms actually reflect those used by different species to control movement, research has shown that a set of relatively simple interaction rules can produce the same global patterns of behavior exhibited in experimental data. The state of group collective motion can be quantified through the use of metrics such as group centroids, measures of group polarization and rotation, along with analysis of the distribution of nearest neighbors (e.g. density plots) to assess the structure of the group in space. Individual level movement patterns are analyzed based on the speed, direction, tangential acceleration and the rate of direction change. Using these measures it is possible to infer a set of interaction rules capable of reproducing the group level dynamics.

While there have been many studies that analyze the aforementioned collective motion properties across a range of animal species, there have been few attempts to understand collective motion and the interaction rules within field-based sports such as soccer and rugby. Qualitatively, players in these field sports exhibit similar group dynamics and collective motion properties to those observed in other species. Players display synchronized movement, execute group turns, maintain fixed distances and cohesion. The players exhibit attraction towards the ball, repulsion from non-ball carrying players and align with their team mates during different states of play. This research analyses collective motion properties in field sports, with the aim of deriving the rules of interaction that reflect those evident with movement data. The ultimate goal of this project is to develop an agent-based model that links the individual-level behavior with the group dynamics to provide a decision support tool capable of accurately simulating gameplay. This initial investigation explores the parameters and individual motion properties of two teams and their players, the emergence of group states and the influence of offensive and defensive phases of play on the group structure. We investigate to what degree the behaviors of team mates influences a player's behavior and the emergence of collective behavior under the constraints of the game rules. Figure 1 reproduces density and polarization analysis of players moving with a speed of at least $2 ms^{-1}$.

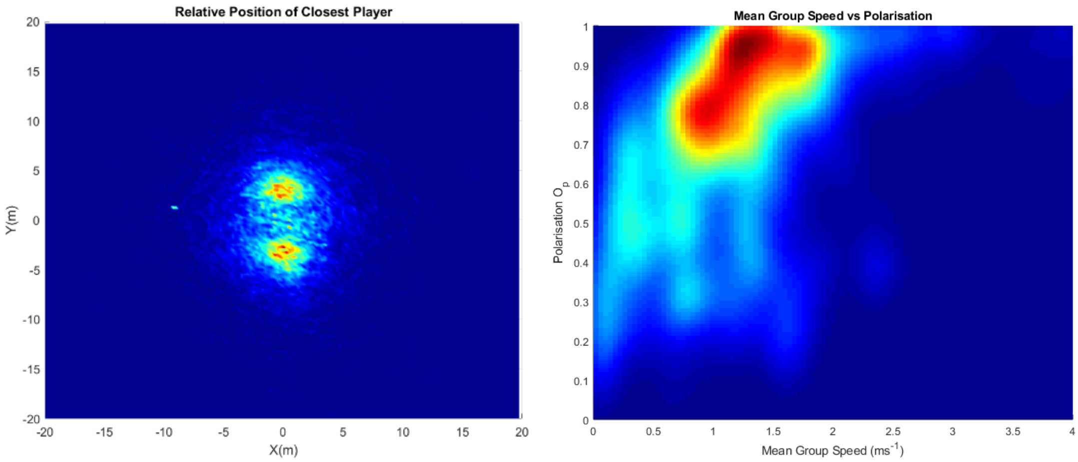

Figure 1. Density plot of nearest player (left) and polarization vs average speed of all players within 8m of focal player (right)

Keywords: *Collective motion, field sport, self-organization, movement patterns, agent based modeling*

Validation of methods for inferring rules of interaction that govern collective motion

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Abstract: Groups of animals coordinate remarkable, coherent, movement patterns during periods of collective motion. Such movement patterns include the toroidal mills seen in fish shoals, highly aligned parallel motion like that of flocks of migrating birds, and the swarming of insects. It is thought that these patterns emerge due to repeated interactions between group members at scales smaller than that of the group; these interactions are sometimes referred to as "rules of interaction". Since the 1970's a wide range of collective motion models have been studied that prescribe rules of interaction where individuals adjust their velocity based on the relative positions and velocities of their group mates. In most cases within-model interactions are some combination of the following broad rules of interaction: *repulsion*: individuals adjust their velocity to avoid collision with near neighbours; *orientation*: individuals adjust their velocity to match that of neighbours that are nearby (but not close enough to crash into); and *attraction*: to avoid group fragmentation, individuals adjust their velocity to move towards far group members. With such rules in action, collective motion models are capable of generating emergent patterns that are visually similar to those seen in real animal groups, but this does not necessarily mean that real animals apply exactly the same interactions.

More recently, a variety of methods have been used to try to infer the interaction rules used by real animals directly from trajectory data. Starting from 2011 researchers have sought to infer the rules of interaction of real animals by applying averaging methods to tracking data. In one of the simplest formulations, the averaging methods determine the mean changes in the components of the velocity of an individual over time as a function of the relative coordinates of group mates. The averaging methods can also be used to estimate other closely related quantities including the mean relative direction of motion of group mates as a function of their relative coordinates. While these methods for extracting interaction rules and related quantities from trajectory data are relatively new and becoming popular, the accuracy of these methods has not been scrutinized. I have addressed this issue by examining how well methods for analysing empirical trajectory data capture the underlying rules of interaction prescribed and simulated by an important self-propelled particle model for collective motion - the zonal model developed in Couzin, I. D., Krause, J., James, R., Ruxton, G. D., and Franks, N. R. Collective memory and spatial sorting in animal groups. *Journal of Theoretical Biology* 218, 1 (2002), 1-11.

The Couzin model is a discrete time simulation model based on three zones of interaction (repulsion, orientation, and attraction) centred on each individual. The size of the zones can be manually controlled to produce computer simulations of swarms, parallel motion, mills and fragmenting groups. To validate methods used to infer interaction rules from experimental data, I first performed a large number of simulations using the Couzin et al. model with varying zone sizes. I then applied the averaging techniques for inferring rules of interaction previously only applied to real world trajectory data to my simulation data, and examined if and to what extent the averaging techniques reveal the known, prescribed, model rules of interaction.

In this presentation I will explore the results of my analysis. In particular, the averaging methods used to infer rules of interaction and the mean relative direction of motion of group mates as a function of relative group mate locations correctly capture the rules of interaction that were prescribed in the model. Further, examining mean changes in direction over time of individuals as a function of both distance to other group mates and the differences in directions of motion between a focal individual and group mate can be used to identify a zone of orientation; this form of analysis has not been applied to real world data previously. Finally, I found that changes in individual's direction of motion over time rendered as function of both the relative location of group mates and the angular difference between an individual and its group mates reveal elements of both individual rules of interaction, and emergent group level patterns of movement.

Keywords: *Collective motion, emergent pattern, tracking data, angular difference, alignment*

Two-patch model for contact process: migration extends the survival region of species

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Abstract: Biospecies usually live in spatially separated patches. Recently, the population dynamics in such patchy environment have been studied extensively. We pay attention to contact process (CP) which is one of simplest ecosystems; both birth and death processes of a single species are carried out on a lattice. In the present paper, we prepare two lattices (patches), and study metapopulation model for CP. Inside respective patches, the birth and death processes of agents (individuals) are carried out. Between patches, agents can migrate. Previously, many authors applied reaction-diffusion equations. Conventional migration method is a diffusion process: migration usually occurs from high-density to low-density patch. However, we apply a refined migration model. A distinct point of the present article is to apply a nonlinear migration; namely, an agent moves into an empty cell. The migration is impossible, if there is no empty cell. We explore the population dynamics depending on mortality rates. If the mortality rate exceeds a critical value (μ_c), the species cannot survive. All mean-field models take the same value of μ_c, irrespective of migration rate. In the case of spatial migration model, however, μ_c takes a higher value with the increase of migration rate. Hence, the survival parameter region of species on lattices is extended by migration.

Keywords: *Birth and death process, metapopulation, Agent-based model, dynamic phase transition, finite sizes of patches*

Identifying significant differences in the rules of interaction that govern collective motion

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Abstract: The spectacular patterns of collective animal movement have been, and remain, a long standing and major interest in many branches of science, including biology, mathematics, physics and computational science. It is thought that the emergent patterns of coordinated motion are the consequence of individuals applying simple rules to adjust their velocity based on the relative locations and movements of nearby group members.

With their origins in the 1970s, the dominant methods for examining hypotheses about simple rules of interaction leading to coordinated, and sometimes complex, group motion have been discrete time self-propelled particle models. Common to many of these models are interaction rules chosen such that individuals will adjust their velocity to: avoid collisions with nearby neighbours, align their direction of motion with group members located at intermediate relative distances, and move towards other group members that are at relatively greater distances.

In the last decade advances in automated visual and GPS tracking methods have led to the exciting development of techniques for estimating the local rules of interaction used by real animals to coordinate collective motion directly from observational data. Analysis of tracking data, particularly of birds or fish in motion, suggests that the form of interaction rules chosen in self-propelled particle models is indeed plausible, with real animals adjusting their velocities consistent with collision avoidance at short range, matching directions of motion, and attraction to distant group mates. However, the mechanics of real interactions differ in detail to those adopted in models, even if the broad principles appear the same.

One of the new class of methods for estimating rules of interaction from tracking data is an averaging method that identifies how individuals adjust their velocity as a function of the relative coordinates of other group members. Thus far, studies using this method have focussed on interactions where all individuals are treated as being the same. In reality, groups of moving animals are likely to be comprised of individuals with differing levels of motivation to find food, seek mates or shelter, and to explore, as well as individuals with a degree of idiosyncrasy to their pattern of movement. All these factors can lead to differences in the patterns of movement of individuals, and therefore it is reasonable to explore if there are any differences in the rules of interaction between individuals within a group that belong to different categories (for example, hungry group members versus those that have recently fed to satiation).

In this talk I will describe a set of randomisation methods designed to identify statistically significant differences in the rules of interaction used by individuals that belong to different categories. The test statistics for these methods are the mean, median, and maximum separation between the functions that describe the changes in an individual's speed and direction of motion (the components of velocity in polar coordinates) for individuals in different categories. I will use the randomisation methods to examine differences in interaction rules between pairs of eastern mosquitofish (*Gambusia holbrooki*) where one fish dominates spatial leadership positions, and the other follows. In concert with this work, I will examine the reliability and convergence of the randomisation methods connected to each test statistic.

Keywords: *Collective motion, rules of interaction, randomisation methods*

Extending agro-food supply chain to address sustainability: Application to wine industry

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Abstract: Food production-consumption is one of the most energy and resource intensive activities. It accounts for 25-30% of the total global anthropogenic greenhouse gas emissions, according to the 2019 IPCC report on Climate Change and Land. Regardless of the ecological footprint of conventional agriculture, a growing number of farmers adopt this system to achieve the economies of scale. Although the application of chemicals such as pesticides and fertilizers can increase the farm yield and reduce the production costs, they have irreversible impacts on ecosystems, environmental resources and public health.

For example viticulture, since the introduction of chemicals in the 19th century, has significantly contributed to a wide range of environmental issues, particularly those related to land and water pollution. Organic agriculture as a part of the solution can partly moderate the overall environmental impacts of vineyards by increasing biodiversity and improving the quality of soils. Wines produced with organically grown grapes are not only less environmentally harmful, but they are healthier with higher content of antioxidants (30%). Despite the health and environmental benefits of organic wines, their global market share is lower than 10% with only 5% of the world's vineyards organically certified. Conversion to organic vineyards is hindered by significant upfront costs for gaining organic certifications, lower crop yields in comparison to the conventional and high risks of harvest loss due to diseases. Without additional support and incentives from consumers, it is unlikely that organic conversion can be financially viable for farmers. Consumer choices and their willingness to pay more for organic wines can offset initial investments and motivate farmers to establish organic vineyards.

To explore how changes in consumer behaviour may impact the wine production process and influence the behaviour of supply chain players, we propose the "extended sustainable supply chain" (ESSC) framework (Figure 1). Our ESSC framework explicitly accounts for feedbacks between different actors along the supply chain and for potential shifts in demand driven by cumulative impacts of changing preferences of heterogeneous consumers, which may in turn affect supply.

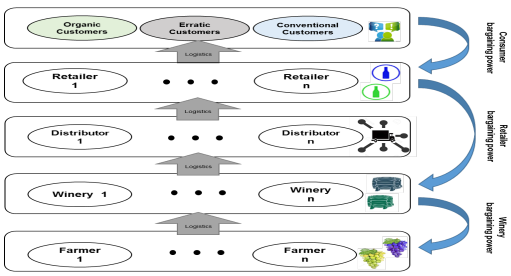

Figure 1. Extending wine supply chain to account for consumer choices (the ESSC framework)

In this study, we then analytically investigate the performance of ESSC by developing a decision support tool, in which the adaptive behaviour of vineyards, wineries, distributors, retailers, and customers is explicitly modelled. We rely on the integrated modelling approach that combines agent-based modelling, discrete-event simulation and system dynamics to operationalize the ESSC framework. The tool provides estimates of economic, environmental and social performance of the supply chain under different scenarios of behaviour change and interventions. It can be used to guide evidence-based policy making in the food and agriculture sector, accounting for incentives that promote sustainability on both demand and supply sides.

Keywords: *Sustainable supply chain, complex systems, environmental behavior, multi-scale modelling*

Simulating the interactions with boundaries and barriers in collective motion models

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Abstract: Collective motion and behavior is a common phenomenon that can be seen across a variety of biological systems that range in scale from cells moving within living organisms, crowds of people interacting within thoroughfares, through to herds of large mammals. Interactions between these individual entities and their environment can give rise to spectacular, self-organizing, visual displays that emerge in the absence of any apparent centralized control. There have been many studies that reproduce his phenomena by describing the movement patterns in terms of the rules that govern the interactions between individuals participating in the collective behavior. The most common approach used in these simulations consists of a zone-based model, where individuals move away from others close by (i.e. repulsion to avoid collision) and align and/or move towards individuals at greater distances to maintain the direction and level of cohesion observed. The application of this relatively simple scheme has proven sufficient to generate simulated output that has been successfully matched to observable measures from experimental data such as polarization, rotation, turning rates, total group area and distributions of nearest neighbors.

Within many systems in nature, collective groups interact with boundary regions and obstacles that can influence individual behaviors and change the observed collective dynamics through the duration of the interaction. Obstacles and boundaries can take the form of impassable barriers (e.g. walls, fences etc.) that cause collective groups to compress, potentially resulting in an increased collision rate, or permeable boundary regions that individuals are able to cross, but with a strong desire to return to within the bounded region (e.g. side lines on sporting fields, pedestrian lanes). For the latter, individuals may not be able to perceive the boundary before crossing, resulting in a desire to re-enter the bounded zone only after crossing. There have been relatively few studies that simulate the interaction of moving groups with boundaries and barriers.

This research investigates simulations for different boundary/barrier scenarios by applying the mechanics of Craig Reynolds' classic *Boids* agent-based collective motion model. This model simulates collective group motion by applying forces that represent repulsion, alignment and cohesion to individual agents, producing emergent collective group dynamics that reflect those observed in many biological scenarios. Figure 1. Demonstrates the effect of a boundary zone (outside the marked square) that agents are able to cross into, but with a simulated desire to return to the zone inside the boundary. In this scenario, the forces of alignment and cohesion are suspended while agents are outside the bounded are to model a situation where returning to within the bounded zone supersedes that desire to maintain group formations.

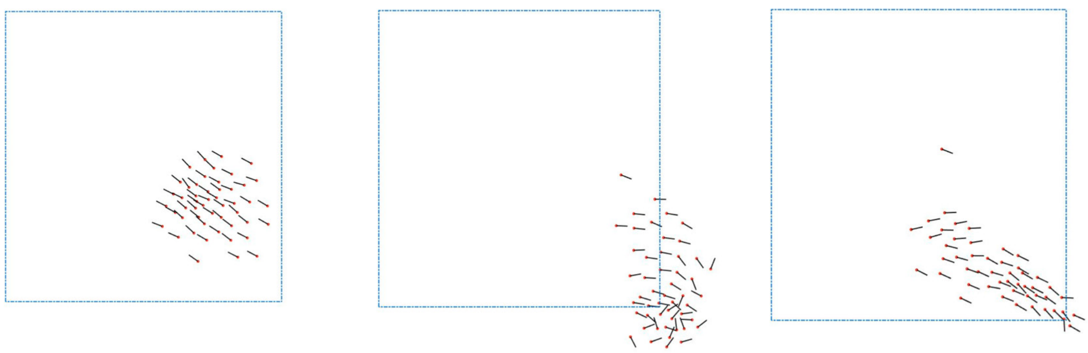

Figure 1. The interaction between a simulated group of individuals and boundary indicated by blue square. The first frame (left) shows the group in motion approaching the boundary zone, the second frame(center) shows the group adjusting its motion to return to the bounded zone and the final frame (right) shows the group resuming normal collective behavior within the bounded zone.

Keywords: *Collective motion, collective behavior, Boids, artificial life*

Using cedar GRASP to simulate pasture utilisation in historical grazing trials in northern Australia

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Abstract: Nutrition affects the reproductive performance of beef breeding females, but the optimal level of pasture utilisation for cow herd production in northern Australia is unknown. Historical grazing trial and reproductive performance datasets are being used to quantify the effect of pasture utilisation rates on reproductive performance. This paper describes the methodology to simulate pasture utilisation using the Mt Sanford grazing trial in the Victoria River District, Northern Territory, as a test case.

The Mt Sanford grazing trial included eight paddocks ranging in size from 4 to 12 km^2 for between 5 and 13 years. Average annual rainfall during the trial was 761mm. More than 90% of rain falls between November and March. The vegetation is a mixed tropical grassland dominated by *Astrebla* spp. (19%), *Aristida latifolia* (18%), *Iseilema* spp. (12%), *Dichanthium* spp. (11%) and *Chrysopogon fallax* (11%). The soil is a basalt derived vertosol. Cedar GRASP was used to model annual pasture growth and utilisation. Parameter sets from six SWIFTSYND sites at the trial site provided the start point for paddock level calibration. Interpolated climate files from SILO data drill and station rainfall provided daily climate data. Satellite derived persistent green cover was used to estimate foliage projective cover. Cattle records were used to estimate intake. Field estimated total standing dry matter (TSDM) measured at the end of the growing season (April / May) and at the end of the dry season (October) was used to calibrate paddock pasture growth (Figure 1). An independent dataset of satellite derived fractional ground green cover clipped to paddock boundaries was used to calibrate site green cover (Figure 2). Modelled green cover is a critical component for modelling pasture growth. The good correspondence between simulated and satellite green cover (r^2=0.90) suggests satellite green cover can be used to calibrate pasture growth for datasets where there are no pasture yield observations. Satellite green cover can identify when growth starts and ends each year and when simulated growth is unreliable, such as in in 2005 when satellite green cover reached a higher peak than simulated green cover. This suggests GRASP underestimated growth that year, possibly due to differences between site and station rainfall.

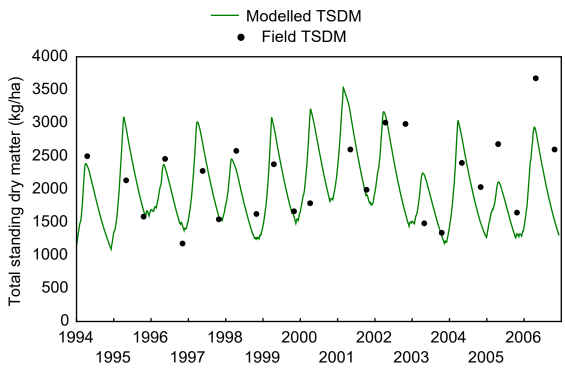

Figure 1. Observed vs. simulated TSDM using GRASP for a paddock at the Mt Sanford

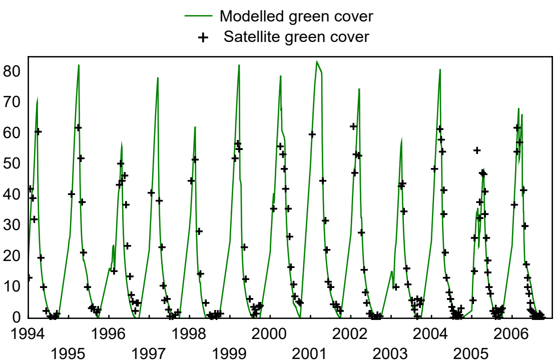

Figure 2. Satellite derived vs. simulated green cover using GRASP for a paddock at Mt Sanford

This approach will be used to retrospectively estimate pasture growth and utilisation for 28 historical grazing trials representing more than 500 herd years. The resulting modelled pasture utilisation will be used in a meta-analysis of the effects of pasture utilisation on beef cattle breeder performance across northern Australia.

Keywords: *Pasture utilisation, northern Australia, GRASP*

Improving evapotranspiration estimation in pasture and native vegetation models using flux tower data, remote sensing and global optimisation

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Abstract: GRASP is a biophysical model of soil water balance, pasture growth and animal production developed for northern Australian grasses in wooded and non-wooded systems. The intention of this work is to improve predictions from the GRASP model of evapotranspiration, soil water balance and subsequent pasture biomass and cover in tree-grass systems. This work feeds into the operational modelling system of GRASP that is disseminated through the FORAGE and AussieGRASS online systems, available at the Long Paddock website (https://www.longpaddock.qld.gov.au/forage). The GRASP model operates at 3 different scales: Cedar GRASP (paddock scale), FORAGE (property scale) and AussieGRASS (continental scale for Australia). The Cedar version is used for model development and research on grazing trials in Queensland and the Northern Territory. FORAGE is an online system for Queensland that generates and distributes customised PDF reports with information for individual properties. Currently over 2000 reports are requested per month for use by extension providers (government and private), consultants (valuers, agents), researchers (universities and government) and land managers. AussieGRASS products are currently used within the Queensland government to assist with drought declaration assessments and a monthly Climate Outlook and Review delivered through https://www.usq.edu.au/research/environmental-sciences/qdmc-drought

This paper documents the parameterisation and improvements to GRASP for estimating evapotranspiration in tree-grass systems. GRASP was overestimating the daily rate of evapotranspiration, particularly in wooded systems during the first days after rainfall events, with evapotranspiration often exceeding 1.3 times pan evaporation (Allen et al., 1998). Model partitioning of evapotranspiration into soil evaporation, grass and tree transpiration also needed adjustment to prevent excessive water loss. Incorporating daily measurements of evapotranspiration from TERN flux tower data provides the capacity to evaluate and improve the estimation of evapotranspiration in GRASP. Model changes include incorporation of satellite-derived fractional ground cover index for green and total cover in the understorey and persistent green for foliage projected cover to further improve the modelling by constraining estimates of evapotranspiration components. Combining field data with remotely sensed data and a global optimiser in an automated system provides the ability to inform model parameterisation and evaluation. Improving evapotranspiration modelling improves the soil water balance, pasture growth, tree-grass competition and safe carrying capacity, where animal numbers are matched to available pasture. Implications for these model changes and evaluation are significant, as this improves our capacity to model grazing land management issues such as runoff, export of sediment to the reef and sustainable long-term carrying capacity.

Key learnings from the optimisation experiments revealed where the model needed improvements, along with careful consideration of trade-offs in regard to variable weighting when optimising multiple measured data groups (such as soil moisture, evapotranspiration and green cover). Model improvements removed the ‘spikes’ in daily evapotranspiration, compared well to measured data and reduced estimated tree transpiration. Daily estimates of surface soil moisture from remote sensing platforms can be used in model calibration but first require model processes and parameterisation to be appropriate at daily time steps. Calibration of evapotranspiration at a daily time step has not been tested before with GRASP due to the lack of high quality daily data sets, especially from mixed tree and grass systems. These results demonstrate the improvements in GRASP for estimating daily and monthly evapotranspiration in mixed tree and grass systems.

Keywords: *Fractional cover, woody vegetation, parameter estimation, remote sensing, model optimisation*

Bio-economic modelled outcomes of drought-related management strategies in the Mitchell grass region

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Abstract: Cattle and sheep grazing is the dominant land use in Queensland, occupying nearly 86% of Queensland's 173 million hectares. High rainfall variability (inter-annual and decadal) experienced in Queensland, coupled with drought, poses major challenges for the sustainable and profitable management of grazing businesses. Stocking rate flexibility, or the degree cattle stocking rates increase or decrease after good and poor pasture growing seasons, is reported as a key strategy for pasture management in northern Australia. The GRASP pasture and animal growth model and Breedcow & Dynama software were used to model breeding herd dynamics for four stocking rate flexibility strategies for a representative property in the Mitchell grasslands of central west Queensland. Farm management economic models were developed to examine the property-level implications of these drought-related stocking rate strategies, and herd level approaches to restocking and destocking.

A 'Set stocking' (SS) strategy, defined as the "safe" number of cattle carried on a 16,200 ha beef grazing property of specified land types, tree cover and historic climate records for Longreach, was determined in the GRASP model so that the average pasture condition (percent perennial grasses, %P) over the 36-year simulation period (1982-2017) approximated an initial 70%P. The modelled beef enterprise was a self-replacing breeding and growing operation that relied on the production of weaners. Simulated annual stocking rates and steer liveweights from GRASP, and published functions for mortality and conception rates in beef breeding cattle in northern Australia, were used to define herd composition.

Three alternative stocking rate flexibility scenarios were simulated over the same 36-year period. These scenarios differed in the degree to which stocking rates could be adjusted each year in response to changes in the amount of forage (Total Standing Dry Matter - TSDM) available for consumption at the end of the growing season (1^{st} May). They ranged from low flexibility in 'Retain core herd' (RCH), moderate flexibility in 'Drought responsive' (DR) to 'Fully flexible' (FF). Data from GRASP and Breedcow and Dynama were used to develop property-level internal rate of return (IRR) for a 30-year period from 1988-2017.

Over the 36 years, the SS strategy achieved an average pasture yield of 1956 kg ha^{-1} and liveweight gain (LWG) of 120 kg hd^{-1} whilst maintaining pasture condition (70%P). The DR strategy achieved the best average pasture yield, LWG and percent perennial grasses (1884 kg ha^{-1}, 127 kg hd^{-1}, 70%P respectively) compared to RCH (1579 kg ha^{-1}, 108 kg hd^{-1}, 59%P respectively) and the FF strategy (1286 kg ha^{-1}, 98kg hd^{-1}, 48%P respectively). IRR of the stocking rate strategies depended on the degree to which herds were reduced and re-built in relation to drought. Property-level IRR were poor under all strategies where natural increase was relied upon to slowly rebuild cattle numbers after drought (SS, IRR= -0.09%; RCH, IRR= -0.27%; DR, IRR= -1.57%; FF, IRR= -4.44%). Positive investment returns were achieved when the DR herd was rebuilt more quickly through either cattle purchases (IRR=1.70%), steer trading (IRR= 0.50%), or agistment (IRR=0.19%). A positive IRR of 0.70% was also achieved with the FF strategy when purchasing pregnancy-tested in-calf cows to rebuild numbers.

Managing stocking rates annually with a moderate degree of flexibility in a highly variable and unpredictable environment maintained pasture condition and demonstrated the best relative property-level investment returns. The positive IRR associated with purchasing cattle, whilst negative when relying on natural increase, suggests that economic viability is favoured by re-stocking within short time-frames once good seasonal conditions return. The speed at which this could occur without impacting on pasture condition could not be adequately explored through annual stocking rate adjustments. Improvements to the modelling approach to allow dynamic and more frequent stocking rate changes would allow the testing of more complex scenarios and lead to greater insight.

Keywords: *Representative property, stocking rate flexibility strategies, herd management, IRR*

Predicting grassland responses to variable rainfall in Australia: combining traits and processes in an ecophysiological model

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Abstract: Grasslands are a key element of the Australian terrestrial biosphere, covering in total 70% of the land surface. Understanding and predicting dynamics of grassland productivity is thus of great ecological and economic importance. In Australia, the major driver of grassland productivity is rainfall, via effects on key physiological processes such as photosynthesis and leaf dynamics (i.e., greening and browning). Physiological responses to changes in soil moisture availability differ among species, according to their functional traits. For example, species with C3 and C4 photosynthetic pathways differ in their water use efficiencies, while leaf dynamics diverge among species with different rooting depths and desiccation tolerance. Consequently, a quantitative understanding of process responses to water availability, and their dependence on species traits, is necessary for the prediction of within-season dynamics of plant productivity under variable rainfall.

Here, we present a generalisable ecophysiological modelling framework that incorporates physiological processes and traits to predict the dynamics of grassland productivity across Australian landscapes. We first quantify empirical relationships between rainfall, plant physiological processes and associated functional traits using observational data, and then demonstrate how that information can be used to improve model predictions of grassland productivity. Model validation using data inputs across landscapes will allow for a comprehensive evaluation and application of this framework.

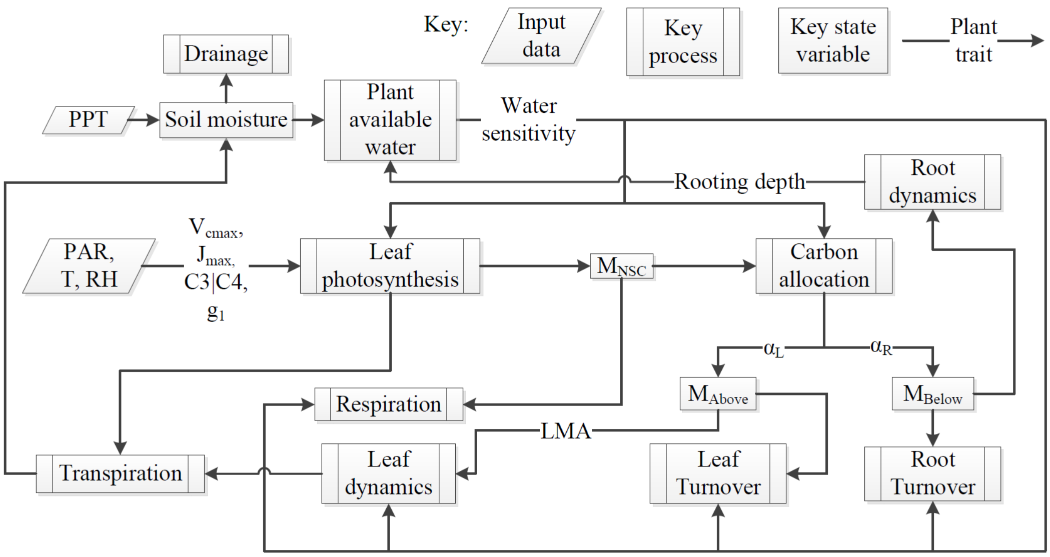

Figure 1. Model flow chart. Key meteorological inputs are precipitation (PPT; mm day^{-1}), photosynthetically active radiation (PAR; µmol m^{-2} s^{-1}), air temperature (T; °C), and relative humidity (RH; %). The major plant traits are maximum Rubisco activity and RuBP-regeneration rate (V_{cmax} and J_{max}; µmol m^{-2} s^{-1}), photosynthetic pathway (C3|C4), stomatal regulation parameter (g_1; kPa$^{0.5}$), leaf mass per area (LMA; g m^{-2}), the sensitivity of physiological processes to drought, rooting depth (m), and the allocation fraction to leaf and root (α_L and α_R; %). The state variables are soil moisture, plant non-structural carbohydrates, above-ground and below-ground biomass (M_{NSC}, M_{Above}, and M_{Below}; g).

Keywords: *Grassland, climate change, trait, process-based model*

Provenance narratives and visualisation to support understanding and trust

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Abstract: We present a system for automatically generating and presenting provenance narratives from World Wide Web Consortium (W3C) compliant provenance records. The interactive narrative visualisation produced allows an analyst or decision maker to explore complex provenance information in a simple, engaging and intuitive manner. Our approach provides a summarised view of the provenance narrative, that can additionally be expanded, collapsed and explored to provide varying levels of detail to the user. Expansion information provides further context to help aid understanding and gain insight. The analyst or decision maker can use the narrative visualisation to explore how: a particular result was achieved; the influence of any particular agent on the result; and the flow-on effects of a particular change in input, constraint or processing that has taken place.

Understanding provenance information in a complex Command and Control system employing AI and automation provides the use case and initial motivation for this work. However, this approach is generalisable, and could be transferred to any W3C Provenance Data Model compliant system. The solution is domain agnostic and capable of handling any type of information, be it tactical, operational or strategic in nature. While still in its early stages, this approach shows promise and may provide a general approach for delivering a level of Explainable AI and transparency, on demand, to a user anywhere where provenance tracking can be instrumented to capture the processing flow of information through a system.

To generate the provenance narratives Rhetorical Structure Theory (RST) is used to provide a framework for achieving and maintaining coherence (Andre 2000). Each element in narrative presentation has a rhetorical relationship to another element that describes its narrative role.

This work presents three main contributions: 1) we examine the novel approach of presenting provenance models as narrative visualisations to increase understanding and trust, 2) we present models to map RST structures to W3C Provenance Data for narrative visualisations, and 3) we present a novel interactive visualisation system based on narrative visualisation that demonstrates the applicability of the proposed approach.

Keywords: *Provenance, narrative visualisation, storytelling, explainable AI, autonomy*

Enabling model management with Source

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Abstract: Source has been endorsed by governments as the National Hydrological Modelling Platform and provides the foundation for many key aspects of water management in Australia. Source models are constantly being changed and improved. When the configuration (project file), inputs or the underlying application is changed, there are often changes to model results. This can have significant implications for the application of the model. Being able to quickly identify what change caused a difference in results can be critical. This paper outlines our approach to good model management.

For model provenance, we recommend one repository per valley/model. This would be for the modellers to use while making any changes to the model and would contain: Source Model (.rsproj file), the binaries for the version of Source used to edit and run the model, plugins that are used (the .dll's), inputs (with "reload on run" where possible), scenario input sets, results of model runs, and the export summary (a text file representation of the model that can be automatically exported each time the project is saved). It can also include scripts for processing inputs and outputs. Modellers would "commit" changes to the models regularly while in development. This also allows rolling back changes when mistakes are made without a loss of work.

To ensure that the model provenance repository is being used as intended and that any mistakes are quickly identified and notified, we use a Continuous Integration (CI) tool. After each change to the model provenance repository, the CI tool runs tests and notifies users when errors occur. This identifies issues such as: users including input data into the model but forgetting to add the data to the repository or users failing to add an updated text-based export of the model. eWater uses TeamCity as its CI tool, it runs all automated testing and deployment processes.

As changes to the Source application are made, over 600 models are run, with selected results compared to a baseline run. This process highlights changes to results caused by small changes to the code and allows eWater to quickly identify problems and the affected projects. This enables eWater to publish a list of Jira issues and affected projects with each beta release, for example, 4.8.0 Regression Test Changes.

eWater can establish an additional repository that monitors when results in your models are affected by changes in the Source application. This additional repository has a copy of each model from the provenance repositories and be used as an additional regression test repository. This allows reporting of when results changes occur and why. This identifies where changes to a model's configuration are required and can explain the different model results when the upgrades to the Source version are made.

Once a repository has been set up, additional tools can be added on top. Specific versions of models can then be distributed through an online tool or users could be allowed to run models with a defined set of changes allowed through scenario input sets.

Keywords: *Provenance, eWater Source, version control*

Minimal requirement provenance capturing workflow systems for hydrological modelling

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Abstract: The NSW Department of Planning, Industry and Environment (DPIE) creates hydrological models to inform policy and decision making in the water sector. High-quality models can be used for decades, and can sometimes be used for purposes not originally envisioned at their creation, delivering additional benefits and insights. In order to maintain the models high quality, new information (such as better data sets) must be incorporated into the model in a timely and accurate fashion. Potential inputs must be assessed and processed consistently and have sufficient metadata for auditing and quality assurance. Historically the manual processes involved with these requirements have contributed to models being expensive to create and maintain.

Well-designed information systems can reduce the maintenance costs of models through simplified data acquisition, repeatable quality assurance and transformation processes, and tracking user activity through time. However, such systems can pose their own management challenges. They require careful consideration of business requirements and capability so that the benefits of adoption remain worth the implementation and maintenance costs.

The Time-series Input Management System (TIMS) is a software system designed to address the challenges of long-term, high volume data management by guiding users through provenance capturing workflows for acquiring and quality assuring time-series of hydrological models. This system is designed to provide:

- An easy to use provenance capturing workflow system that functions without complex software and hardware dependencies.
- A guided workflow-based system that captures sufficient metadata automatically to assemble a provenance trail, and provides a flexible user experience that is of sufficient quality to promote user uptake.

TIMS requirements are simple and the system can be run from a USB drive. User adoption has been promising, and system functionality has been progressively rolled out through DPIE's surface water modelling group. TIMS allows provenance to be both captured and extracted. Introspective workflows and operations that consume provenance information to assist in modelling work have been successfully created, with extensive consultation with technical reference groups to ensure processes embody best modelling practice. Ongoing development on TIMS continues to expand functionality to meet user needs.

Keywords: *Provenance, workflows, hydrology*

Retrospective BIM as an enabler for digital transformation in the built environment: A case study

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Abstract: The emergence and fast development of digital technology have become increasingly important in the Architecture, Engineering Construction, and Operations (AECO) industry. In a global level, the unprecedented global challenges of ever-increasing urbanisation, climate change and global competition call for new ways of designing, constructing and operating cities, buildings and infrastructure. In the UK, digital transformation is considered a strong enabler for seizing the opportunities of the digital economy, managing the increasingly complex assets, maximising on the capacity and skills of the AECO sector workforce, and creating new business models based on emerging technology. Furthermore, it is a critical aspect in achieving the ambitious UK's national construction vision 2025 of cutting Carbon Dioxide (CO2) emissions, reducing cost and time of construction projects

Digital technology is equally important for facility and asset management industry; optimisation of total cost of ownership for assets, reducing asset management risk, improving sustainability performance for the built environment, saving energy are some of the goals that can be attained by developing and embracing digital technology in facility and asset management industry. At the heart of this digital future, is the need for data-driven asset lifecycle management to optimise operations costs, reduce operation risk, improve productivity and efficiency of the way we operate and maintain our built environment. Digital technologies such as building information modelling (BIM) Information, communication technology (ICT), the Internet of Things (IoT) has the potential to create a more digitally enabled asset management. The development and effective diffusion of these technologies in the facilities management industry will not only contribute to the current digital transformation agenda but also prepare for a more digitally enabled future in the built environment using more advanced digital technologies like artificial intelligence and machine learning.

Facility and asset management organisations are now working towards digitisation of their processes, tools, systems and technology infrastructure to extend the capabilities of BIM and the asset data created in the design and construction phases of building lifecycle in the operations phase. Furthermore, many of the computer-aided facility management (CAFM) system providers are updating their systems to use the asset information created by BIM including the Construction Operation Building information exchange standard (COBie), the 3D BIM models and the asset operation and maintenance documentation to support asset operation. It is expected that shortly all the CAFM systems will be BIM ready. However, the vast majority of the current built environment have no BIM. This opens the question; how the existing built environment can be digitised to use the capabilities of updated BIM-enabled CAFM systems and enable more advanced digital technology such as the Internet of Things (IoT)?

This case study is being implemented at headquarter building of a construction and facility management service provider in London, UK. The case study will explore the use of laser scanning and modelling technology to create a retrospective building information model (BIM) for the building. The model will be built using the existing computer-aided design (CAD) drawings of the building, and integrating the laser scanning data into the model, then enhancing the model with asset data for selected equipment that are considered most important for operation. A standard COBie data file will be extracted from the created model and uploaded to the IBM Maximo CAFM system. The case study will provide a detailed analysis of the process of creating this BIM model of the built environment, and discuss the opportunities and limitations of using this retrospective modelling mechanism to enable digital transformation for the current built environment. The study will then present the lessons learned from the case study, and its potential to be used as a standard approach to digitising the available asset data in the built environment.

Keywords: *Retrospective BIM, laser scanning, digital engineering, asset management*

Translation of stranded IP to commercialisable software applications using Workspace

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Abstract: For Australia and many other countries, which have large gaps between their research inputs and economic outcomes from their national innovation systems, understanding where and in what form the IP generated resides represents a significant opportunity. Aside from publication outputs (which are usually the primary measure of research excellence) and registerable IP (patents etc) which form only a small amount of the IP generated, there is significant development of enabling tools and data. However, such IP (termed "stranded IP") can often have value to third parties if these opportunities can be identified, the IP put in a suitable form and then provided to them for use.

Usage of research outcomes and research software can be highly valuable to the right customers if they can be provided in a usable form that is fit for their usage purpose in a cost effective and timely manner. Research IP is typically developed for specific research purposes and projects (most commonly with the aim of publication) with opportunities for translation to third parties either not considered or identified significantly after the form of the IP has been determined.. The form of the IP is usually decided by individual researchers or teams based on what suits their current needs rather than strategically or with the intention of translation or later commercialisation.

It is also common for enabling IP to be part of a larger process or workflow which usually then also involves multiple manual or semi-manual steps. In the modelling and simulation space, this is particularly common in relation to the preparation of model inputs and the analysis, preparation or presentation of outputs. These represent substantial barriers to translation, as potential users judge the cost of expert knowledge acquisition to be too high and the distortions to their internal workflow and decision making processes to be too costly and/or risky.

It is useful to consider research activities as workflow processes, being composed of a series or network of unit operations linked with input-output relationships and execution order dependencies. Typically some or many of these operations or steps will use software components (often including proprietary or open third party sources). The intervening manual steps present strong hurdles to the automation of these semi-manual workflows which inhibit reproducibility and transfer to third parties. It also allows errors in the use of the IP to be introduced. An effective solution is to convert all steps into workflow unit operations that can be manifested in a scientific workflow system. This can facilitate high levels of component re-use, improved collaboration, interoperability of the software components in an extensible and customisable way. This provides the ability to adapt to new and emerging requirements and to customise IP on a per customer basis at comparatively low cost.

This paper explores the nature of stranded IP and the obstacles that limit its exploitation. It then explores how the adoption of a software workflow platform, Workspace in this instance, can overcome a sufficient subset of these obstacles so to provide a low cost pathway from internal research to exploitable software applications and products. A methodology is proposed, based on the capabilities of Workspace, for taking legacy, enabling or stranded IP, particularly in the modelling and simulation space, and building translatable and commercialisable products.

Keywords: *Workspace, stranded IP, commercialisation, IP translation pathway, workflow*

The Bio-Mechanic Workspace plugin: enabling biomechanical measurement and simulation across workflows and software applications

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Abstract: The Bio-Mechanic (BM) plugin for the CSIRO Workspace platform is presented and its benefits are discussed in context with the design principles and strengths of Workspace. The BM plugin facilitates a number of activities for biomechanics science including movement measurement, model personalisation, kinematic analysis, forward dynamics simulation, numerical analysis and visualisation pre-processing. Since this codebase is written as a plugin for Workspace it inherits by design a large range of interoperability, reusability and productivity benefits.

The structure of the BM plugin is presented in context with typical uses of the operations. File readers have been developed which populate model components from popularly used sources (e.g. common simulation package and marker-based motion capture formats). A range of operations can be used to clean input data, such as to reduce noise in movement or force data. Models can be scaled or rigged to surface meshes. Kinematic analysis can be carried out to determine the characteristics of a body movement or the differences between multiple movements. Forward dynamic simulation can be performed to determine the environmental loading on the body and the internal biomechanical loading such as tendon, muscle and joint forces. Results from kinematic analysis or forward simulation can be graphed using custom widgets and visualised in 3D. Operations and workflows are naturally interoperable, using the same datatypes and interfaces, and easily shareable. When combined with a user interface the workflows can be easily developed into standalone software programs.

Four use cases are presented to highlight the benefits of producing biomechanical workflows using the BM Workspace plugin. First, a dataset from the literature is visualised in 3D and the pose of the skeleton and muscles is easily displayed at any of the time instances of the supplied motion data. Second, a simple workflow is presented which uses the same dataset to simulate foot-ground contact during running and to predict the external force on the body and the resulting movement of the body centre of mass. This is a typical high value usage of simulation for biomechanics which is extremely easy to implement and customise for users without a software design background. Third, the use of the plugin to build, analyse, visualise and report on a large and detailed simulation that uses an external solver is described. A coupled biomechanical-smoothed particle hydrodynamics (SPH) simulation is used to study sporting technique improvement where physical experimentation is difficult to perform and quantify. The plugin enables quick model development and analysis which is critical for timely completion of such large simulations. Fourth, a deployed software application built upon the BM plugin is described which combines a database of elite divers and more than sixty diving performances in an interactive virtual experimentation tool for coaches to improve springboard diving technique. Because the software was built in the Workspace environment it is modular, highly interoperable and its design was easily experimented with. As a result, its development was highly agile and productive.

Typical with Workspace plugins, the BM plugin has many benefits inherited from the use of the Workspace environment. The operations, workflows and standalone software are highly interactive and intuitive. Operations and workflows are naturally interoperable and reusable. Linkages with other code bases and solvers is easily achieved and already in place for many popular libraries. Productivity of users is increased by the aforementioned benefits which enables more breadth and depth of scientific inquiry to be completed. Finally, commercialisation and speed to market are improved because the method of use is efficient, restructuring can be done easily and quickly and because workflows can be converted into standalone software with little user effort.

Keywords: *Biomechanics, simulation, Workspace, workflow, motion capture*

Workspace for Industry 4.0

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Abstract: Compared to writing software from scratch, Scientific Workflow Systems (SWSs) provide a more convenient way to acquire data, customize inputs and combine algorithms in order to develop reproducible outputs. Workspace is an SWS that has been under continuous development at CSIRO since 2005 and which attempts to address key challenges faced by the research and commercial communities; researcher/developer productivity, reproducibility of results, collaboration between research teams and portability and interoperability between different computing environments and scientific domains.

One such domain is that of Industry 4.0, commonly referred to as the "fourth industrial revolution". Industry 4.0 centers on the development of "smart factories" where cyber-physical systems and physical processes operate in concert to create a virtual copy (or "digital twin") of the physical world in order to enable (or in many cases automate) decentralized decision making. In such smart factories, manufacturing processes often take the form of a workflow, where devices, data and algorithms are combined in different ways to produce outputs for decision making and automation purposes.

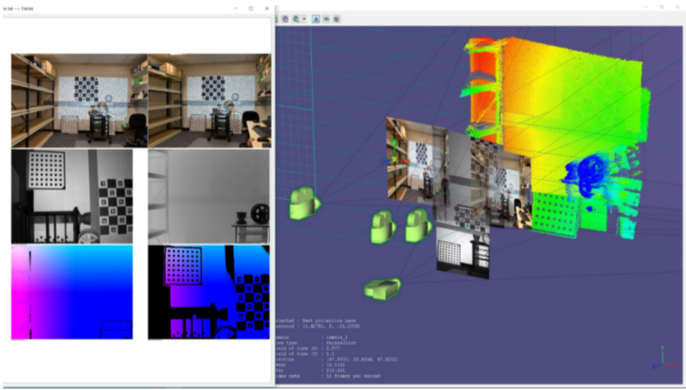

Figure 1. Part of the Workspace-based demonstrator - results of multi-sensor data collection. On the left, the raw image data from the sensors. On the right, DSLR images and point cloud data from time-of-flight sensors are shown in a 3D scene. Points are coloured by depth, where blue is closest and red is furthest away

In this paper, we explore how Workspace, in both design and implementation phases, can provide significant value when creating digital twins using arrays of sensors. An Industry 4.0 demonstrator application is used to highlight challenges and to show how a workflow approach can be used in applications representative of real-world needs. The demonstrator application is specifically focused around the inspection of manufactured components for quality-assurance purposes. In doing so, we will analyse how Workspace addresses the specific challenges that are presented by problems within the Industry 4.0 domain. These include the need to tailor the system to specific manufacturing processes at low cost, the ability to cope with large volumes of streaming data and changes in how the data is integrated and interpreted, developing the skills of operators to cope with the complicated processes involved while maintaining existing know-how, and the need to maintain the integrity of the disparate processes.

We provide a detailed study of those features and plugins of Workspace which are beneficial to the development of Industry 4.0 applications, such as distributed execution, OpenCV, PCL, ZeroMQ plugins, and the ability to create custom applications. These capabilities, along with the Workspace design principles of analyse, collaborate, commercialise, everywhere, align it well with problems in the Industry 4.0 space, allowing the creation of high performing implementations for use in industrial settings.

Keywords: *Workspace, industry 4.0, workflow, manufacturing, inspection*

Fractura – Common modelling platform for multiple hydraulic fracture simulators

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Abstract: The modelling platform 'Fractura' was developed by CSIRO on the Workspace platform[1] to facilitate wider access to novel and emerging hydraulic fracture modelling approaches. Hydraulic fracturing treatments are used for a variety of geotechnical applications such as improving production from shale gas and coals seam gas wells, increasing the permeability of enhanced geothermal energy and in-situ recovery mining systems and to increase the safety and efficiency of block cave and longwall mining. These different in-situ environments and industrial contexts require different modelling approaches to accurately capture the propagation and extent of the created hydraulic fracture network.

Simulation of hydraulic fracture propagation is a complex problem and there are many intrinsic challenges associated with modelling the mechanics of fluid-driven fractures[2]. Advances and new approaches in the field are developed across private, academic and research institutions using different theoretical approaches, written in different programming languages. These emerging models' outputs are often difficult to directly compare and therefore understanding their suitability for various applications can be a challenge. Fractura offers a common modelling platform where multiple hydraulic fracture simulators can be run simultaneously using the same set of input data and where simulation outputs can be directly compared to determine the most appropriate modelling approach for a situation.

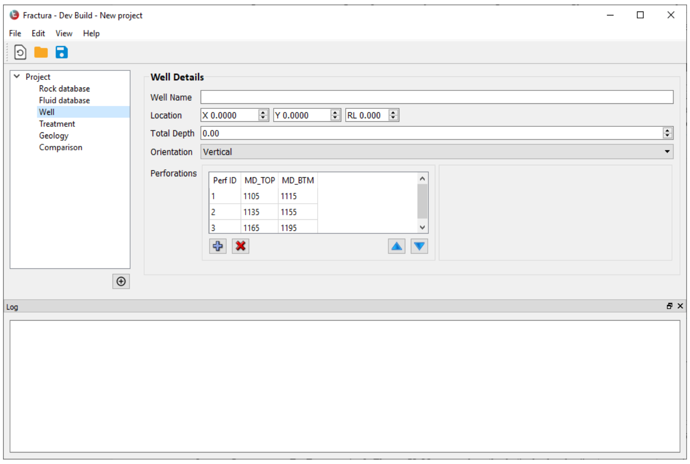

Figure 1. Fractura User Interface

The Fractura platform enables faster transition of promising new modelling approaches from the research environment to pilot scale industry deployment. It also provides a platform for developers to make their models available for others to run, facilitating validation and, where desired, collaboration. Fractura provides end users an intuitive interface to easily run, compare and validate different hydraulic fracturing simulators. As an additional step, if a hydraulic fracture modelling approach is identified as meeting client needs, Workspace can be utilised to create a custom software application tailored to that client.

The initial release of Fractura includes CSIRO's MLP3D model [3] and the PKN, KGD and Radial analytical solutions.

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Keywords: *Hydraulic fracturing, Workspace, numerical modelling, software platform*

Workspace – a Scientific Workflow System with commercial impact

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Abstract: Compared to writing software from scratch, Scientific Workflow Systems (SWSs) provide a more productive environment to automate the

1) acquiring of data,
2) combing of algorithms, and
3) the orchestration of pre- & post-processing, in order to develop reproducible workflows and their outputs.

Workspace is an SWS that has been under continuous development at CSIRO since 2005 and which addresses several key challenges faced by the research and commercial communities. A key differentiator between Workspace and other SWSs is its facilities to supporting commercialisation of IP.

In this paper, we present a short overview of Workspace and its defining features and then describe in more detail some of the newer useability improvements and functionality provided to assist teams of users when creating applications and systems during development and execution – i.e. features and functionality normally referred to as supporting “programming in the large”.

Recent additions have been driven by users creating increasing complex systems: where workflows may contain many operations, applications may use many workflows, and individual workflows may be edited on by multiple people. The additions include:

1) visual miniaturisation of input, output and variable operations,
2) improved loop construction and control,
3) extended workflow comparison, and
4) workflow merge.

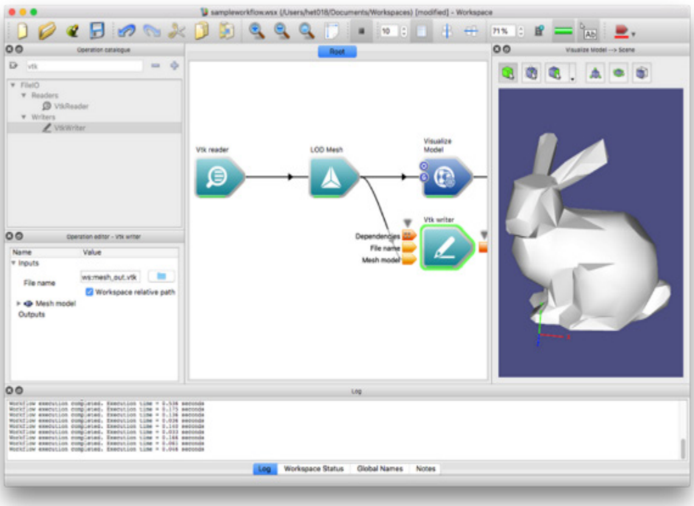

Figure 1. The workspace editor: an interactive workflow editing and execution application.

Keywords: *Workspace, workflow, visualisation, commercialisation*

An integrated optimisation functionality for Workspace

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Abstract: Scientific Workflow Systems (SWSs) allow scientific workflows, networks of operations connected with directed data flows, to be efficiently developed, executed and shared with others. By leveraging the built-in functionalities of SWSs, users can focus on creating domain specific content such as physical models. Workspace (Watkins et al. (2017)) is a scientific workflow and application development platform developed by the CSIRO. Users construct workflows using an intuitive graphical interface. Input and output variables can be viewed and modified using graphical interface objects called widgets which are implemented using the Qt framework [1]. A suite of plugins that provide operations, data types and widgets for tasks such as data analysis, file IO, 3D rendering and scripting are provided out-of-the-box, and users can create their own custom plugins. Wizards for creating new plugins, operations, data types and widgets are available, allowing the C++ source code skeletons to be automatically created, minimising development overhead.

Mathematical optimisation involves utilising numerical algorithms to find the best solution to one or more objective functions, and is a functionality of great utility across many scientific and engineering disciplines. Optimisation functionalities have previously been implemented in a number of SWSs. For example, optimisation frameworks have been developed for Taverna (Crick et al. (2009)), Kepler (Abramson et al. (2010)) and Nimrod/OK (Nguyen et al. (2017)). Prior to the current work, an integrated optimisation functionality has not been available in Workspace. Whilst parameter sweeps could be set up and controlled from within Workspace, applying algorithmic optimisation methods required either executing the workflow from an external optimisation tool, or the development of optimisation logic in a custom plugin as done in the present work. There is considerable value in developing such an integrated optimisation functionality for Workspace due to its unique capabilities as a SWS — in particular, the ability for Workspace to allow research codes to be transformed into professional standalone applications. For example, standalone applications have been developed using Workspace for bushfire spread prediction (Spark, Miller et al. (2015)), modelling of elite-level diving (Dive Mechanic, Cohen et al. (2017)), and solar power plant design (Heliosim, Potter et al. (2018)). The present work would allow optimisation to be incorporated into such standalone applications with minimal reformulation of existing plugins and workflows. Furthermore, Workspace supports remote execution and parallelisation of loops that could be used to allow the rapid execution of complex objective functions.

In previous work (Potter et al. (2018)), a plugin, workflow and standalone application called Heliosim has been developed using Workspace for the optimisation and simulation of central receiver concentrating solar thermal (CST) facilities. The central receiver CST involves the use of heliostats (mirrors that track the sun) to reflect solar radiation onto a central tower-mounted receiver located at the focal point, where the thermal energy can be stored and used for power generation or industrial processes. The core functionality of the Heliosim software is the simulation of heliostat optics using Monte Carlo ray tracing and the simulation of receiver heat transfer via a finite-volume model. This core functionality is used to form objective functions for the optimisation of the heliostat field layout, tower height and receiver geometry. The C++ code underpinning the integrated optimisation functionality presented in this paper was originally part of the numerics library used by the Heliosim software. This functionality has now been exposed as the Optimisation Loop operation in a newly developed Numerical Methods plugin for Workspace. The motivation for creating a devoted numerical methods plugin is the potential for its more general use beyond the current audience for the Heliosim plugin, which is mainly within the CST research group at CSIRO. In this paper, the software design of the Optimisation Loop operation is described, and an implementation of the Nelder-Mead simplex algorithm is validated. A case study is then presented where up to seven constrained variables describing the geometry of a beam-down CST reactor for producing hydrogen are simultaneously optimised to maximise annual energy output.

[1] https://www.qt.iotest

Keywords: *Scientific workflow, optimisation, solar energy*

ArcWeld: A case study of the extensibility of software applications built using Workspace architecture

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Abstract: The ArcWeld software is a "factory-floor" application, designed to provide simulation of welding capability to users with little or no knowledge of the underlying mathematics or physical processes involved. As such it is an excellent demonstration of how stranded IP, which is only usable by an expert, can be converted into a user-friendly software application, presenting complex inputs and results in a simple-to-use and easy-to-understand form. ArcWeld is built on the powerful Workspace workflow framework, which presents an easy pathway for researchers to turn their scientific software and manual processes into an end product usable by a wide range of customers.

This paper describes the challenges facing the developer when producing, maintaining, and enhancing software such as ArcWeld, and how the Workspace ecosystem can mitigate many of the obstacles facing a researcher whose aim is to make their solver's modelling and simulation capability more widely available. This is illustrated using a case study, in which the changes and extensions required by a new commercial customer are described. The changes included a wider range of process parameters and the requirement for in-built graphics. This required additional input and output files as well as many changes to the graphical user interface.

A detailed description of how Workspace was used to facilitate these changes is provided. The product was previously built on Workspace; this had ongoing benefits in terms of extension and customisation. It is demonstrated that Workspace provides the flexibility and ease-of-use to allow the software to be modified without the need for any major rewriting or reworking. This streamlined the process and reduced the likelihood of errors, ensuring that the modification was fast, inexpensive and painless.

Keywords: *Arc welding, graphical user interface, workflow, Workspace, computational fluid dynamics*

Scalable Cloud-based scientific research platforms as a pathway of technology delivery in exploration geophysics

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Abstract: Earth scientists rely on large datasets for analysis, interpretation and prediction of rock properties at different scales. In our case study, we partnered with a team of geophysicists that use electromagnetic exploration techniques extensively for remote detection and measurement of subsurface electrical conductivity structures for a variety of geophysical applications such as mineral exploration and groundwater detection. Airborne electromagnetic (AEM) data are spatially and temporally dense, often covering hundreds of kilometres. With data sampled every 0.2 seconds and on average 30-50 measurements taken at each site, a typical AEM survey is in the order of millions of individual stations, with tens of millions of measurements. A sequence of data processing steps and numerical codes are applied to invert collected data into conductivity-depth information which provides a geoelectrical image of the subsurface. This requires a sophisticated computing infrastructure for efficient operation which might be prohibitively expensive for many small- to medium-sized exploration companies. It also restricts researchers' access to early adopters who are more agile and flexible in the uptake of new technology than large companies but can lack resources and expertise to set up the necessary infrastructure. Herein we address both limitations by offering early adopters access to cutting-edge techniques and providing researchers with a link to end-users.

We developed a platform that enables visual interaction with geophysical data and allows seamless integration with complex numerical codes at various scales – from a desktop-based data processing to the inversion of hundreds of kilometres of AEM data in a Cloud, private compute cluster, High-Performance Computing (HPC) facility or a combination of those. The architecture, in which everything is packaged as a Docker container, allows individual applications to run in different environments without recompiling. Containers are dynamically built using an open declarative scripting language and can be shared via a common Docker Registry. The containerisation also eliminates potential library dependency conflicts as each container represents an isolated execution environment that is configured for a specific program. Our processing toolkit scales massively from a desktop to a Docker Swarm Cluster to a Cloud with ease and shrinks to nothing when computing resources are no longer in use, thus offering a cost-effective option on a pay-per-use basis with a low entry barrier. The computational load can be dynamically balanced through a range of means, e.g., growing the Docker Swarm or delegating computationally heavy tasks to a dedicated HPC server (Figure 1). The approach develops lightweight Cloud-hosted front-end applications tailored to specific needs, thus not limiting users to a particular application. It has been successfully trialled on two different projects and demonstrated a high degree of component reuse and low cost in provisioning Cloud resources. Complex numerical codes or legacy programs can also be packaged as Docker containers and reused in multiple applications.

The proposed approach is cost-efficient and enables a mutually beneficial link between researchers and explorers. For researchers, it offers a flexible technology delivery channel where research results can be packaged and tailored to specific customers' needs with little overhead while protecting researchers' intellectual rights. For exploration companies, the use of commercial Cloud providers eliminates the costs and risks involved in infrastructure investment.

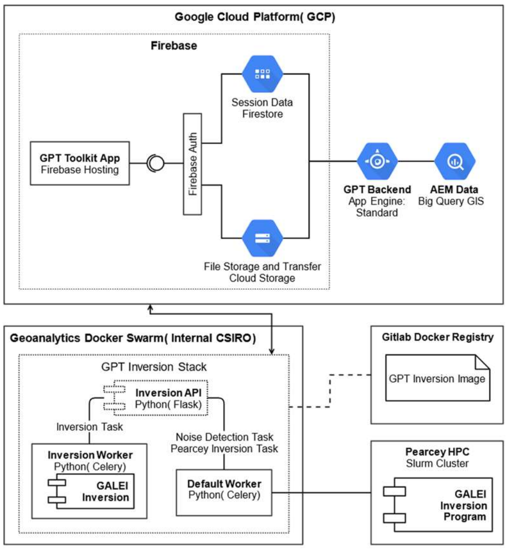

Figure 1. Deployment diagram of the GPT across a combination of Google Cloud Platform, internal CSIRO Docker Swarm Cluster and HPC.

Keywords: *Geophysics, cloud infrastructures, exploratory data analysis, human-computer interaction.*

Closing the loop on modelling's role in natural resource investment planning

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Abstract: A perennial problem of natural resource management is how to most effectively use a limited budget to achieve the greatest environmental and social benefit. The field of water quality and environmental modelling has provided great insights to allow the consequences of alternative investment strategies to be investigated. However, the modelling process is largely divorced from the decision-making process. Policy makers and planners indirectly use the outputs from models in the planning process. The planned investment then becomes operationalized via on-ground investment plan. The end result is an on-ground implementation that is two steps removed from the modelling process and there is no ability to easily integrate the 'as-constructed' implementation as a modelled scenario. We propose to close the loop in the modelling-planning-operationalise workflow sequence. We illustrate the workflow approach using a recently developed web tool, based on simulated annealing and combining numerical and spatial data, used by Seqwater; the Catchment Investment Decision Support System.

Our approach in developing the Catchment Investment Decision Support System has been to create a single platform that completes tasks for different user groups across the natural resource management investment planning workflow (Figure 1). To ensure the application is fit for purpose for the users, we have restricted access to various components of the platform based on a user's roles. The platform has been designed for external and internal stakeholders, policy level staff, catchment modellers and operational staff who implement on-ground activities. The platform can be used to store data, create optimal intervention scenarios, create pragmatic versions of scenarios, publish web based visualisations of those scenarios for a broad audience, develop on-ground work plans and integrate 'as constructed' activities back into the model input data.

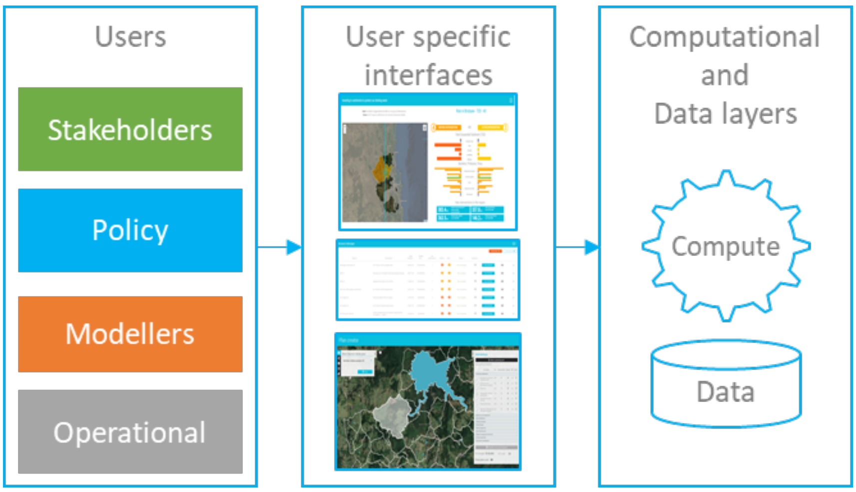

Figure 1. User roles based approach to access interfaces and computational and data layers of the platform

Keywords: *Catchment investment, optimisation, workflow, operationalise, drinking water quality*

A study on content-based geographic data sharing strategy for interdisciplinary research

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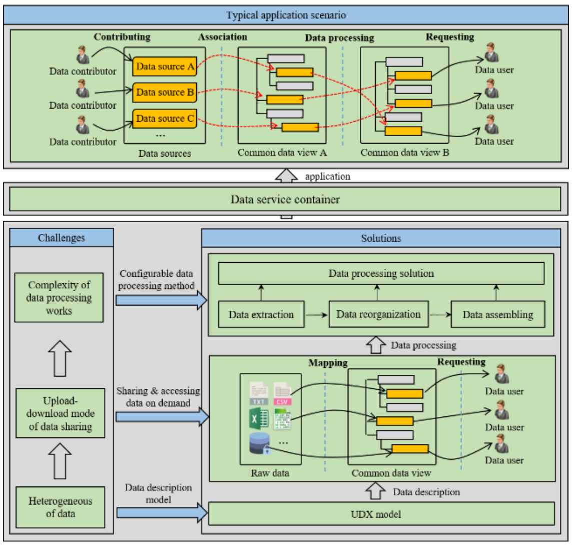
Abstract: With the growing attention of comprehensive environmental issues recently, a number of geo-analysis model and related data resources have appeared on the Internet, which aims to couple multidisciplinary models to solve complex geographic problems. Although there are many model integration frameworks and specifications have been developed to support model invocation through the web, the study of data sharing standards or specifications are still relatively weak. Geographic data is the intrinsic description of geographic phenomenon and process, which provides the raw materials for geographic researches. However, it is difficult to share geographic data among researches with different backgrounds in the open web environment, due to the heterogeneity of geographic data and the complexity of data processing methods. This paper proposed a content-based geo-data sharing strategy, which includes: data description method, data sharing on-demand, configurable and data preprocessing methods and component-based data visualization method. The proposed data sharing strategy aims to provide an efficient and flexible framework, which can support content-based geo-data sharing and reusable data processing services generation for various application requirements in comprehensive geographic research.

In the proposed framework, there are two basic fundamentals, the UDX model and data processing service. The UDX model is employed to describe geo-data in an unambiguous way, and the data processing service provides the methods to preprocess geo-data in the open web environment. With the UDX model, geo-data providers can share their data on-demand, and they also need to provide the corresponding data processing services for accessing the shared data by users in open web environment. Based on the data processing services, users can extract the required data from multiple data sources, then reorganise and assemble them to form a new data source. The data visualization solution is composed by several visualization components, and each component has been bound to a specific type of data source. A study case of community flood simulation using SWMM is used to examine the practicability of the framework in this paper.



The designed framework is highly modular and extensible. By using the framework, researchers from distributed areas can easily share the data, and the unified access of data processing services make it quickly to processing the data for comprehensive applications, thus reducing the difficult of interdisciplinary research.

Keywords: *Data visualization, integrated modeling, data processing service, UDX model*

Service-oriented interfaces design for distributed geographical simulation resources usage in the web environment

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Abstract: Modelling is an important method for geographical research. To date, massive geo-analysis models from different domains are developed to simulate various geographic phenomena and processes, and solve many kinds of geographic problems. Geographical simulation usually has many kinds of resource involved (e.g. model resource, data resource, computer resource etc.). So, collaborative modelling for simulation task has become a popular and effective method when working with a diverse range of resources. However, the existing simulation resources are tightly-coupled in simulation and hard to be shared. With the development of the Internet, service-oriented sharing and reusing of geo-analysis models on the Web is an effective way for scholars and experts to collaborate on complex geographic phenomena and simulation processes. There are a large number of related techniques for wrapping and publishing models as services on the Web, such as Web Process Service (WPS), Basic Modelling Interface (BMI) and OpenMI. Nevertheless, these sharing modes only barely meet the requirement for the different kinds of resources to be assembled in one geographical simulation task.

Shown as figure 1, this article analyzes the using scenario and aims to design a series of service-oriented interfaces in simulation task for different geographical simulation resources, which include model knowledge resources, model usage resources, computing resources and data resources. Such interfaces can support the geographical simulation resource sharing and reusing between model users and can be further used in resources assembling on the Web. This article also discusses the advantages and disadvantages of service-oriented and component-based design. Finally, we provide some different kinds of use cases, such as a Fire Dynamic Simulator model and a Random Forest model for remote sensing image classification, to show how the interfaces can benefit geographical simulation resource sharing and reuse in applications for simulation task building.

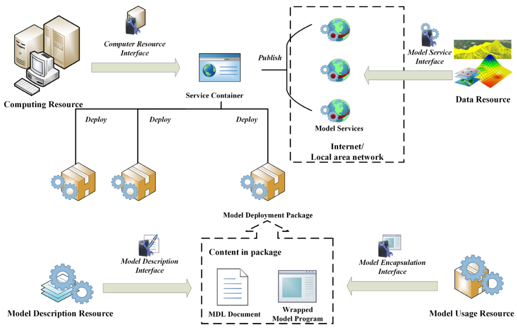

Figure 1. Task design for geographical simulation sharing and reusing

Keywords: *Simulation resource sharing, service-oriented interface, distributed simulation, web*

Using natural language processing for classification of lithological borehole data

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Abstract: In the last decades there has been a shift in the focus of sciences. While the collection of data was the main priority of the last century, in the current century the main purpose is its synthesis, digitalization, and subsequent processing to find hidden patterns that help us to explain reality. This new "digital era" has implied the development of new branches of science to solve problems that require huge amounts of data. However, there is a significant quantity of data stored as qualitative descriptions which have been rarely used for scientific purposes. Such is the case of geologic and soil descriptions, which comprise a textual representation of the different materials with which scientists were dealing with in their studies. Until recently, there was no way to deal with such information, but the emergence of Natural Language Processing (NLP) has implied that it can be numerically handled in a vectorial space. One of the most common approaches of NLP is the creation of a vectorial representation of words or "word embeddings". Since NLP has rarely been applied to the geosciences, we present a method that allows classifying geologic materials through word embeddings.

The dataset used in this study corresponds to the bore log descriptions contained in the Australian Groundwater Explorer of the Bureau of Meteorology, which contains over 100,000 boreholes with over 800,000 lithological descriptions. The dataset used has its own classification of the lithologies. However, 546 different lithological classes can be found in the original dataset, several of which aggregate lithologies based on irrelevant characteristics, such as color or weathering stage. Therefore, an improvement of the classification is required. The borehole descriptions were pre-processed and the GeoVec model (a GloVe model) allowed us to obtain the word embeddings. Subsequently, all word embeddings constituting a lithological description were averaged to obtain a single embedding by description. The original dataset was semi-manually classified into 18 main lithologies using regular expressions. Additionally, a Multilayer Perceptron (MLP) neural network was built and trained using the description vectors and the classes semi-manually obtained. The evaluation of the classification was assessed through accuracy, f1, and balanced accuracy scores.

Results show that the use of word embeddings leads to accurate results in the lithological classification even when using just a small fraction of the original dataset. It also allows the quantification of uncertainty, which is mainly caused by the ambiguity of the descriptions. This uncertainty cannot be addressed by using a manual classification. Future research involving the fully automatization of the textual classification by combining unsupervised algorithms remains a key priority.

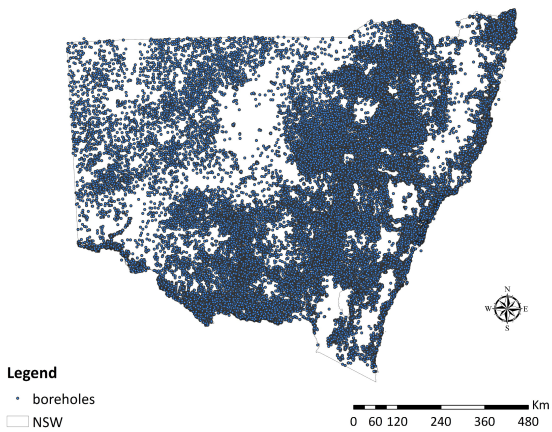

Figure 1. Distribution of boreholes located in NSW, Australia.

Keywords: *Word embeddings, lithologies, classification, natural language processing*

Comparing regular expression and deep learning methods for the classification of descriptive lithology

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Abstract: Characterisation of the geometry and internal architecture of aquifer systems forms an important part of many groundwater investigations. Lithological descriptions from driller's logs are an essential component of this characterisation. Analysing driller's logs manually is a tedious, error prone and repetitive task in many hydrogeological projects. Yet, the analysis of these lithological descriptions is the main, sometimes sole initial step informing the subsequent workflow with ramification in the rest of the data analysis towards groundwater systems characterisation.

The python package for exploratory lithology analysis 'ela' (https://github.com/csiro-hydrogeology/pyela) aims to facilitate and reproducibly capture the workflow leading to the geometry of aquifers for groundwater modelling. The 'ela' package inherited from its ancestor implementation a method where pattern matching with regular expressions (*regexp*) had been used to classify lithology descriptions into primary and secondary lithology classes. This *regexp* method remains the default method used to assist geoscientists in the classification of descriptive lithology. The field of machine learning (ML) has seen the rise over the past five years in the performance of other approaches for text classification, including natural language processing (NLP) combined with deep learning (DL).

We compare the accuracy of the *regexp* technique against a new approach using the natural language processing toolkit *nltk* and a DL model, using a Long-Short Term Memory (LSTM) layer and the TensorFlow platform. The detailed computational workflow for this paper is available online in a notebook. The training/validation data is a lithology classification of 177632 log descriptions in the Condamine River catchment, previously performed by a hydro-geologist. The DL method achieves an accuracy of 86%, where the *regexp* method achieves 79%. Figure 1 compares the confusion matrices of the DL and *regexp* methods. The *regexp* method outperforms the DL by 5.5% for the classification of basalt, but DL is more accurate in the classification of the three other classes. DL is most markedly better at accurately predicting the classes 'alluvium' and 'unknown'.

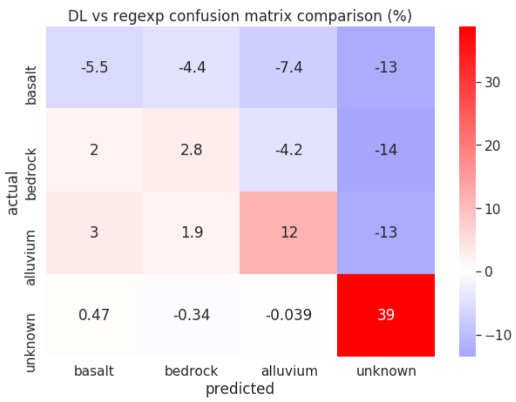

Figure 1. Comparison of classification performance of deep learning and *regexp* methods. If red on the first diagonal, or if blue elsewhere, DL performs better than *regexp*

The end goal of this study is to devise novel techniques to aid geoscientists in the classification of unlabelled data or with limited labelled data. Notwithstanding the validation data used in this study, we have yet to test the transferability of a trained DL model to a different basin without using training labelled data. From this initial performance comparison using labelled data from Condamine catchment, the NLP+DL technique appears promising to capture some additional useful information from descriptive lithology that would be difficult to extract using only regular expressions.

Keywords: *Lithology classification, text analysis, NLP, deep learning, regular expressions*

Image recognition for vehicle traffic analysis at intersections

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Abstract: We have been conducting research on traffic simulation for traffic jam analysis. Before building a traffic simulation system, it is necessary to perform actual road observations. However, in the past, a great deal of labor has been required to acquire data on vehicles running on the road. In this study, we propose a method to easily obtain car driving data by using image recognition.

In recent years, cameras are becoming smaller and higher performance. Therefore, an image can be taken from a free position. In general vehicle traffic, traffic congestion often occurs due to the flow of vehicles at intersections. Therefore, in this research, we decided to take a bird's-eye view from the top of the building in contact with the intersection. We have taken many images from buildings in the city and made them sample images so that the vehicle can be recognized from the overhead position. And we built a system to track the position of the vehicle by using image recognition technology by machine learning. This system makes it easy to analyze the movement of vehicles at intersections. This vehicle tracking system in the intersection constructed makes it possible to measure the transit time of the intersection. Furthermore, by using this system, the traveling time of a group of vehicles can be automatically measured.

Our experimental system makes it easier to analyze the driving characteristics of vehicles at intersections. Then, we compared the YOLO (Redmon, J., et al. 2016) adopted for the image recognition method this time with the OpenCV cascade classifier used so far, and analyzed the characteristics of each method.

As a result of this research, we will be able to analyze vehicle traffic in detail, so that we can construct an effective traffic simulation, and will be able to perform more accurate traffic congestion analysis.

Keywords: *Traffic flow, image recognition, traffic analysis*

Contextual digital soil mapping using CNNs

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Abstract: Digital soil mapping (DSM) has been widely used as a cost-effective method for generating soil maps at different scales, from field to global. However, current DSM data representation rarely incorporates contextual information of the landscape. DSM models are usually calibrated using point observations intersected with spatially corresponding point covariates extracted from raster files. Here, we demonstrate the use of convolutional neural networks (CNN) in order to incorporate contextual information surrounding a soil observation to significantly improve the prediction accuracy over conventional DSM models. We describe a CNN model (Figure 1) that takes inputs as images of covariates centred at the soil observation location and explores spatial contextual information by finding non-linear local spatial relationships of neighbouring pixels. Unique features of the proposed model include: input represented as 3D stack of images, data augmentation to reduce overfitting, and simultaneously predicting multiple outputs. Using a soil mapping example in Chile, the CNN model was trained to simultaneously predict soil organic carbon (SOC) at five depth intervals across the country. In the example of country-wide mapping at 100 m resolution, the neighbourhood size ranging from 3 to 9 pixels (equivalent to 150 to 450 m) was more effective than at a point location and larger neighbourhood sizes. A similar influence distance was reported by several studies exploring the spatial autocorrelation of SOC using geostatistical methods. In most DSM applications, the prediction of deeper soil layers is influenced by the fact that covariates mostly represent surface conditions. In our model, thanks to its multi-task architecture, it was possible to predict deeper soil layers more accurately, utilising information from the top layers as regularisation. Overall, in this study, we observed an error reduction of 30% compared with conventional techniques that only used point information of covariates. The resulting prediction also has less uncertainty. Furthermore, the use of this data structure with CNN seems to eliminate artefacts generally found in DSM products due to incompatible scale of covariates and sharp discontinuities due to tree models.

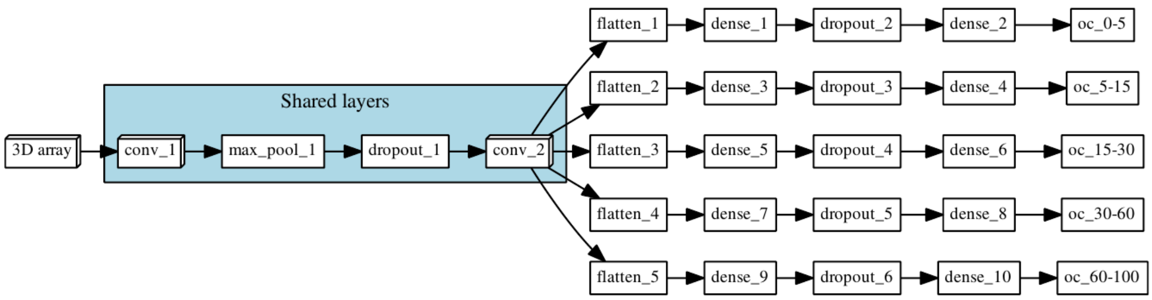

Figure 1. Architecture of the multi-task network to simultaneously predict soil organic carbon at 5 depth intervals.

Keywords: *Neural networks, soil organic carbon, soil modelling*

Predicting recirculating flow over an idealized dune using machine learning

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Abstract: Coastal foredunes play an important role in protection of land, assets and communities. Understanding of these complex systems usually comes from physical measurements that are often site specific. The use of numerical modelling using Computational Fluid Dynamics (CFD) has been increasing as it can enable holistic three-dimensional data and visualization of the wind flows. Generalised conceptual models of flows over foredunes can then be built and revised over time as more data becomes available. Obtaining this data is limited by resources and is also weather and location dependent. A systematic study is being undertaken to explore what happens when the flow transitions across the beach and encounters the stoss face of the foredune. A simple dune shape (pseudo two-dimensional) is used in CFD simulations to tease out the relationship between dune parameters such as height, crest width and slope (lee and stoss) with environmental conditions (wind speed and direction). The number of simulations required is unfeasible due to the large number of variables and resource intensive because of the large geometries and their associated meshes. Mayo and Wakes have already demonstrated that surrogate models, developed using CFD simulation data, can predict wind velocity for flow over a complex topography and wind turbine wakes to good accuracy. Therefore our work asks if machine learning has the potential to be used in place of CFD to predict the occurrence of recirculation in key positions around our dune system with an associated saving in time and resources?

Five simulation parameters (dune form/slope, dune height, crest width, wind angle and wind velocity) were defined, each with between two and five different values. This yielded a total number of distinct parameter combinations of size 450. From those combinations, we selected 100 parameter combinations via latin hypercube sampling, and we ran one CFD simulation for each of the selected combinations. At the conclusion of each simulation, approximately 100 sample points at different (x,y,z) positions were used to measure two targets, the shore normal wind velocity component (v; target 1) and reattachment angle (atan2 (v/w); target 2). Negative values for the targets are indicative of recirculation of the wind flow over the dune. This yielded a total dataset size of 10,400 examples with eight features per example (the features being the five parameters and the three coordinates) along with the two targets that varied across the simulation volume. Next, we used machine learning classification techniques to predict the sign (positive or negative) of each target at each of the sampled (x,y,z) positions. To estimate the generalisation performance of different models, we performed simulation-grouped ten-fold cross validation. Models that we tested included logistic regression, multi-layer perceptrons, and various decision tree ensembles. To account for the class imbalance (9733 positives vs. 667 negatives for target 1, and 6752 positives vs. 3648 negatives for target 2) we also tested various preprocessing techniques such as oversampling (e.g. SMOTE) and re-weighting examples based on class frequencies. Our cross-validated results indicated that gradient boosting with 2,000 decision trees and SMOTE achieved the best overall accuracy with F1=0.588 for target 1 and F1=0.894 for target 2, calculated with respect to predictions that the target will be negative. F1 is the harmonic mean of precision and recall with a value of 1 indicating perfect precision and recall.

Following model selection, we retrained the best model on the complete dataset and ran additional simulations for further validation. Our results indicate that the model is able to predict which simulations will have a high number of negative target values before the simulation is run, with good accuracy for target 1. By being able to predict the existence of recirculation around the dune form for all combinations of dune parameters and wind variables the use of machine learning significantly reduces the number of CFD simulations required. The use of surrogate models in combination with CFD has the potential to be a powerful combination for environmental fluid mechanics where geometries are large and there are complex environmental conditions that influence the flow.

Keywords: *Turbulence, machine learning, recirculation, wind flows, computational fluid dynamics*

Decreases in flooding due to drier soils

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Abstract: Climate change is changing the risk of flooding with implications for design of infrastructure and management of our water resources. It is generally accepted that as temperatures increase, extreme precipitation will also increase resulting in more severe flooding. However, this is not what historical records show us. In Australia, and across the world, there is significant evidence of decreasing annual flood maxima, despite increases in extreme rainfall.

Flooding is dependent on multiple factors with cascading uncertainty as water travels from rainfall above the catchment to the eventual streamflow at the catchment outlet. The resultant flood will depend on the duration of rainfall, its intensity, the temporal and spatial pattern of the rainfall, and the antecedent moisture conditions, that is, how wet or dry the soil is before it rains. These factors, coupled with catchment specific characteristics, such as stream connectivity, vegetation and and soil properties, will all interact with each other to determine the size of the flood event.

In this work we combine three data sets produced by the Australian Bureau of Meteorology. Streamflow from the Hydrologic Reference Stations (HRS) is matched with catchment rainfall from the Australian Water Availability Project (AWAP), and soil moisture from the Australian Water Resources Assessment Landscape (AWRA-L) model. We sample flow events based on rainfall and match the rainfall to the resultant streamflow as well as the soil moisture prior to the rainfall to understand how antecedent soil moisture is (a) modulating flooding, (b) changing with climate change, and (c) affecting flooding with climate change.

Our results demonstrate that annual maxima floods are decreasing in southern Australia due to decreases in soil moisture despite increases in extreme rainfall, while in the tropics, the flood increase is greater than what can be explained by extreme rainfall increase alone. However, the impact of changes in soil moisture modulating flooding depends on the size of the catchment and the intensity of the rainfall. For events rarer than 10% AEP, we arrive at a scenario where the increase in rainfall intensity outweighs the extra rainfall that is soaked up by the increasing soil moisture deficit. The result is a 'worst of both worlds' scenario whereby the rare flood events that are used in design of infrastructure are increasing, but smaller events, critical for water supply and dam storage are decreasing.

Keywords: *Flooding, extreme rainfall, soil moisture, trends, climate change*

Block-based artificial neural networks for flood inundation modelling

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Abstract: Floods are one of the most frequent and destructive natural hazards in the world, but they also have positive impacts on floodplains, such as delivering environmental water crucial for local eco-systems. Therefore, it is important to understand, assess and predict floods in order to mitigate risks and maximise their benefits. Flood inundation models are often required to serve this purpose. However, current flood inundation models are computationally intensive and are not well suited to use in real-time operation or in applications that require many hundreds or thousands of simulations. Therefore, a fast and accurate flood inundation model is needed. Simulation models based on data-driven approaches, such as artificial neural networks (ANNs), can potentially be used for this purpose as they have been successfully used as emulation models in environmental modelling. Traditional ANNs only rely on the use of lagged inputs to take time series behaviour of floods into consideration. In order to include continuous time series information in the development of the ANN models, a block-based ANN modelling framework is proposed for flood inundation modelling in this study.

In this framework, a model is first developed to predict water depth in the next time step based on current and previous flow and water depth information, and then this model is repeatedly applied n times across a forecast horizon of n hours to predict water depth n hours ahead. The n-hour forecast horizon can be determined based on average travel time of water. Two different approaches for error update (named MB1 and MB2) can be used in the training process. Both MB1 and MB2 used the Levenberg-Marquardt algorithm (LMA) to optimize the ANNs. The main difference between the two approaches is that for MB1 calibration error is estimated after the step within the n-hour window, whereas, for MB2 calibration error is estimated at the end of the n-hour window. A Multilayer Perceptron (MLP) model is used in this study.

The performance of the block-based modelling method was also compared to a traditional point-based ANN, named MP, via a real-world case study. A section of the Burnett River in Queensland, Australia was used. Streamflow and flood inundation depth are available for 2 historical and 7 design flood events. The flood inundation depth data were simulated using a 2D TUFLOW model provided by the Hydrology and Risk Consulting (HARC). The results in Figure 1 (Plots a-c) demonstrate that all 3 ANNs can approximate the 2D hydrodynamic model well. The comparison between the 3 models (Figure 1d) shows that block-based ANNs have better overall performance than point-based ANN across the study area considered, with MB2 slightly over-performing MB1. However, in data-sparse region across floodplains, the traditional point-based ANN (i.e. MP) outperforms block-based ANNs. This is mainly because the block-based ANNs have more complex structure, which requires more data for model calibration. Therefore, it is important to consider data availability when selecting model structures, as sometimes "the less is the better".

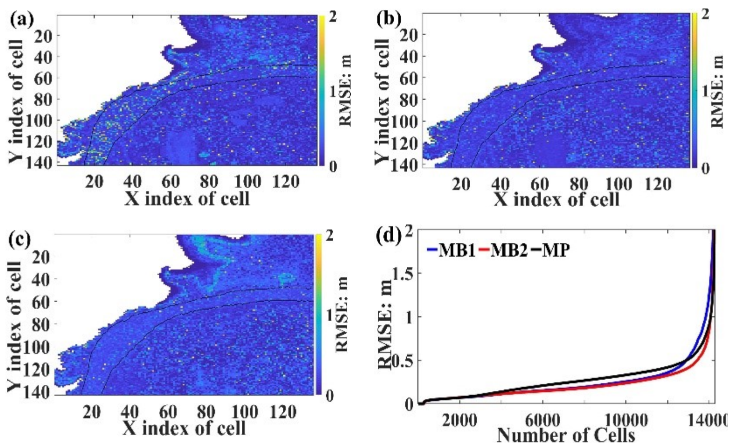

Figure 1. (a) Root mean square error (RMSE) in validation set of MB1; (b) RMSE in validation set of MB2; (c) RMSE in validation set of MP; (d) Comparison of RMSE in validation set among 3 models

Keywords: *Flood inundation modelling, surrogate model, block-based ANN, point-based ANN*

Mixed methods of sensitivity analysis for studying the response surface and uncertainty of hydrologic models

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Abstract: Investigating the response surface of hydrologic model outputs is essential for understanding the associated hydrologic system and how model parameters and inputs affect those outputs. Sensitivity analysis has long been applied in environment modelling to aid model development, parameter screening and uncertainty quantification. In this study, sensitivity analysis is used to study the response surface of two hydrologic models: SWAT (Arnold et al., 1998) and TopNet (Bandaragoda et al., 2004). SWAT has been widely used for watershed hydrologic modelling and water quality simulation, while TopNet has been used as a national hydrologic model for flood prediction and flow simulation in New Zealand. Sensitivity analysis methods range from parameter screening methods (i.e. Morris method; Morris, 1991), to machine learning (Gaussian Processes) based on the Sobol' method (GPSobol; Oakley and O'Hagan, 2004), and Active Subspaces (Constantine and Diaz, 2017). Results show that for both hydrologic models, all three methods can be efficiently applied at a low computational cost. The Morris method can effectively screen out insensitive parameters, while whereas the Active Subspace method can identify the parameter optimization direction, and GPSobol can quantify the parameter contributions to modelling objectives, including parameter interactions. Similar results between Active Subspace and GPSobol demonstrate that both methods are not only useful for sensitivity analysis but also in exploring the response surface of these two applications (SWAT and TopNet). Machine learning methods like Gaussian Processes and Polynomial Chaos efficiently emulate desired Quantities of Interest of the response surface of the original model. The resultant emulations can be used not only to undertake sensitivity analysis but also to undertake uncertainty analysis, which is especially useful when the original model has long runtimes that inhibit sufficient sampling of the parameter space. Thus it can be used as a substitute for the original model. But the emulation can also identify insensitive parameters to fix in the original model and narrow the ranges of sensitive parameters for sampling (Yang et al.,2017).

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Keywords: *Response surface, sensitivity analysis, uncertainty analysis, hydrologic modelling*

Machine learning approaches to improve and predict water quality data

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Abstract: Changes in water quality have a variety of economic impacts on human and ecosystem health. The widespread use of in-situ high-frequency monitoring instrumentation enables a better characterisation of water quality processes, leading to more meaningful decision making. The large amount of data collected by the high-frequency sensors creates new opportunities for machine learning methods to better understand data-intensive processes in aquatic ecosystems and improve data streams coming from sensors.

CSIRO's DigiscapeGBR project aims to help protect the Great Barrier Reef (GBR) by enabling upstream sugarcane growers to make better nitrogen fertiliser management decisions, supporting water quality improvements which are critical to meet ecological targets for protecting the health of the Reef's ecosystems. Current studies based on machine learning in the DigicapeGBR project to improve data and predict future water quality are mainly focused on the following:

- Water quality prediction.

  The development of reliable water quality predictions is critical for improving the management of aquatic ecosystems. Predicting the response of coupled biogeochemical and physical systems is challenging due to the complexity and non-linearity of these systems. Thus, a machine learning approach may be accurate in predicting water quality as it accounts for non-linearity.

- Water quality data imputation

  Missing data are unavoidable in water quality monitoring systems. Most data analysis methods require complete data as inputs. Incomplete data can produce biased or wrong results, with negative effects on the conclusions drawn from the water quality data. Classical methods for filling gaps in the data perform poorly when consecutive data points are missing. Thus, there is a need to compare the performance of a machine learning approach against classical imputation methods.

- Water quality outlier detection

  The data collected by environmental sensors can be noisy and have outliers due to sensor malfunction. These anomalies make the data more difficult to analyse and interpret. Therefore, the identification of atypical observations is an essential concern in water quality monitoring. Typical methods for outlier detection have low detection rates given the high variability in water quality data. Thus, there is a need to investigate the performance of a machine learning approach for outlier detection in water quality data.

In this paper, we introduce and summarise the machine learning based modelling work we have been investigating for solving the three challenges described above. For water quality prediction, neural network models based on artificial neural network (ANN), recurrent neural network (RNN) and convolutional neural network (CNN) have been developed to forecast changes in dissolved oxygen (DO) and other water quality variables in rivers draining to the GBR. For water quality data imputation, we proposed a sequence-to-sequence imputation model (SSIM) for recovering missing data in high-frequency monitoring systems. The SSIM uses the state-of-the-art sequence-to-sequence architecture, and the Long Short Term Memory Network (LSTM) is chosen to utilise both the past and future information for a given time. For water quality outlier detection, we have been investigating neural network models combined with the wavelet decomposition. All the models show promising results in solving some of the challenges around water quality data management and prediction.

Keywords: *Artificial intelligence, neural network, data driven, time series, great barrier reef, nitrate*

Causality and cointegration of stock markets within the Asian growth triangle

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Abstract: This paper explores the co-integration and causality relationships amongst the Asian Triangle stock exchange indices. These Asian triangle regions consists of the eight key markets of Shanghai, Shenzhen, Hong Kong, Thailand, Philippines, Malaysia, Korea, and Indonesia. In applying modern unit root and co-integration econometric techniques that will allow for structural breaks over our sample period of data (October 2002 to August 2018), we found that there is no co-integration within these markets except for that between Shenzhen and Shanghai. By using Granger causality tests, Johansen, and impulse response functions, we will show that stock price changes in Hong Kong have more impact on Asian triangle markets than that of any other market. More specifically, price changes in the Philippines market can be used to gauge the succeeding movement of the other Asian markets excluding Shenzhen and Shanghai. We develop various potential and current relationships within these markets that would lead one to further empirical research. Our overall finding was that Hong Kong being the epicenter still plays an important role in assisting and motivating emerging markets as shown through our impulse response testing and would therefore not yet rule out the importance of developed economies.

Keywords: *China, causality, cointegration, stock returns, Asian market*

An improvement of jump diffusion model for Japan Nikkei 225 indexes and its application to estimating the stochastic volatility

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Abstract: We investigate the daily share prices of Nikkei 225 indexes to identify jump times using a jump diffusion model, which consists of the Black-Scholes model with stochastic volatility and a compound Poisson process. We consider how to separate jump times from the observed data. From the obtained results we propose a new type of jump diffusion model for the share prices and a robust scheme to estimate the stochastic volatility.

Keywords: *Jump diffusion model, Nikkei 225 indexes, stochastic volatility, historical volatility*

News release and volatility spillovers across Chinese financial markets

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Abstract: The development of capital market in China has attracted much attention from practitioners and academic researchers due to its rapid growth in the past decades. One predominant milestone was the listing and trading of the first Chinese financial futures contract, which was launched by China Financial Futures Exchanges (CFFEX) in 2010. Later in 2015, CFFEX issued another two index futures including SSE 50 Index and CSI Small Cap 500 Index. Although the development of index future trading can provide the investors with additional hedging instrument, it remains unclear of how trading stock index futures in the futures market affects the stock market. Due to the instability caused by the future market, the Chinese regulatory authorities blamed the 2015 stock market crash on speculators' "malicious short-selling" in the futures market and described the index futures trading as "weapon of mass destruction" to market stability.

This paper examines the dynamic of the stock index spot market and the future index market by providing an insight into the price discovery process and the volatility spillover effects between 2006 and 2018 using CSI300, A50 and SSE50 stock indexes, as well as their correspondent future rates in the Chinese markets. To investigate issue related to market efficiency, we also assess how public information arrival through news releases affects the dynamic correlation between the spot and the future markets. Methodologically we employ the Vector Error Correlation (VEC) model to examine the price discovery process, and adopt the diagonal BEKK multivariate GARCH model (DBEKK-MGARCH) and the diagonal VECH multivariate GARCH model (DVECH-MGARCH) to examine the volatility spillover effects between the index spot market and the future index market in a multivariate setting with the consideration of asymmetric effects.

The results indicate that the stock index spot rates have the dominant predicting power in the price discovery process, whereas the future index rates are not significant. Also, volatility spillover effects are found significant and bidirectional between the index spot rates and the future index rates, and the conditional volatility in the spot and future markets are highly time-varying and persistent. Our results confirm the presence of asymmetric volatility effects, where market is more reactive to the same magnitude of shocks and persistent volatility is higher in an uptrend (bull) market than in a downtrend (bear) market. The co-volatility spillover effect originated from the spot markets is relatively larger than that from the future markets. Moreover, our results show that news release has significant and positive association with the dynamic conditional correlation between the index spot market and the future index market. We also find evidence that market participants are more likely to consider macro-economic news, financial market news and firm specific news jointly rather than relying on single type of news in their decision-marking process. The results suggest that incorporating the impact of public news arrivals in the conditional correlation measure can potentially improve the conditional correlations and the hedging strategies in these markets. These findings also have important implications for regulatory authorities when monitoring how news affects the stock market and the future market, and also for the hedging strategy and portfolio management.

Keywords: *Index market, Future market, Price discovery, Volatility spillover effect, Public information arrival*

Inadequate corporate profitability and marketability efficiency: A case of Vietnam manufacturing enterprises

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Abstract: The manufacturing sector plays an increasingly pivotal role in the development of Vietnam. In the context of economic integration, Vietnam manufacturing enterprises receive abundant investment and market-expansion opportunities that enhance their operating profits and market values. With the aim of supporting corporate managers to position their firms competitively in the market as well as make wise management decisions, this study employs bootstrap two-stage data envelopment analysis technique to investigate the profitability and marketability efficiency of 102 listed manufacturing firms on Vietnam stock market from 2007 to 2018. The study also applies fractional regression models for panel data to identify the determinants of Vietnam manufacturing firms' efficiencies.

Based on the empirical results, the study reveals that Vietnam manufacturing firms obtain higher profitability efficiency scores (0.888) than marketability efficiency scores (0.527) during the study period from 2007 to 2018. Thus, listed manufacturing enterprises in Vietnam should place more emphasis on market attractiveness to boost their enterprises' market value. Besides, different manufacturing sub-sectors achieve different levels of profitability and marketability efficiency during the study period 2007 to 2018. Specifically, the modern (high-tech) firms achieve higher average marketability efficiency scores from 2007 to 2018 and better profitability efficiency performance in the recent years from 2015 to 2018 than the traditional (resource-intensive and labour-intensive) manufacturing firms. The results also show the diverse and significant impacts of firm age, headcount, institutional ownership, cash level, and leverage ratio on profitability and marketability efficiency of Vietnam manufacturing enterprises.

Keywords: *Bootstrap two-stage DEA, Fractional regression model, Vietnam manufacturing sector*

Empirical distribution of endogenous inefficiency: Case of municipal hospitals in Japan

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Abstract: This study attempts to check the shape of inefficiency distribution for the case of municipal hospitals in Japan. We asume hospital behavioral model, instead of inefficiency distributions, in stochastic frontier analyses (SFA). The standard procedure to analyze industry-mean inefficiency in SFA is to assume one of plausible inefficiency distributions such as half-normal or exponential. In the framework, the assumed inefficiency distribution summarizes all the latent information on inefficiency, including the mechanism through which the inefficiency is generated. The most important feature (except for goodness of fit to the data) of the inefficiency distribution is that it is one-sided: A clearly consistent property with economic theory.

Then, do we have to leave everything beyond the one-sidedness to the goodness of fit? One of the possible theoretical approaches to this problem is to specify the mechanism that generates inefficiency. The widespread manner, which relates the predicted individual inefficiency to the exogenous covariates, helps to select relevant ineffiency factors. But the selection of the covariates often lacks theoretical background.

Building a model that generates inefficiency (that is, inefficiency is described as an endogenously determined equilibrium) for each industry is itself cumbersome. But once the mechanism is specified, individual inefficiency is determined as a function of exogenous variables. This function provides information not provided in usual two-step SFA. The former approach helps evaluation not only of the effect of various covariates, but also of behavior principle.

Inefficiency is observed because DMUs sometimes need to do something more than profit or cost optimization. This may be the case especially in public utility or non-profit industries. Healthcare provision system in many coutries are typical examples. In previous studies on public hospitals, hospitals are assumed to have preference on the quality of their service and financial status. We apply these settings to compute the endogenous ineffi-ciency, using the data of municipal hospitals in Japan. We find that the mode of the inefficency distribution is positive, which suggests we need more careful selection of distributional assumoption in empirical works.

Keywords: *Stochastic frontier, endogenous inefficiency, hospital inefficiency, public hospitals*

Investment location selection: Strategies for foreign direct investment in Vietnam

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Abstract: Foreign direct investment distribution is unequal in terms of economic activities as well as among regions, provinces and cities within countries. Therefore, understanding reasons why foreign investors favour a location over others are necessary for policymakers, governments, and international investors. Although determinants of selecting investment locations have been studied, different determinants are identified in different countries. Additionally, studies on the investment location selection within a country are limited, especially in Vietnam. This gives rise to questions which factors make a location more attractive to the foreign investors and whether they have similar effects in different provinces and cities within a country.

This paper aims to investigate the determinants of investment location selection at the provincial level in Vietnam based on foreign investors' perspectives. The four groups of factors include human capital, economic, provincial competition and institutional, and infrastructure. The study uses panel data set with 63 Vietnam provinces and cities from 2000 to 2015. The ordinary least squares estimation supported by the Hausman test is employed in the empirical estimation. The results of models with and without a lag term are robust.

Unlike many previous studies, we employs retail sales of goods and services instead of gross domestic product to represent economic growth at the provincial level. The provincial competitiveness index is employed to represent economic governance of provinces and cities. The investment incentive policies index is proposed as the aggregate index of three types of investment incentives (free land, income tax exemption, and import tax exemption) instead of considering only tax incentives. The country risk index is proposed to represent the political stability and security. Ranking of provinces and cities based on their socio-economic conditions is employed to investigate the different effects of the determinants in different areas in Vietnam.

Surprisingly, this study shows that foreign investors tend to invest more in areas with fewer investment incentives. Additionally, foreign direct investment flows into Vietnam increased after the financial crisis in 2008 as foreign investors may take advantage of lower value currency and lower cost in the areas offering high investment incentives. The effect of infrastructure development on investment location selection is weaker in areas under more difficult socio-economic conditions. This study suggest that Vietnamese policymakers and provincial governments should invest more in education and training, control exchange rate and inflation rate, enhance investment efficiency, maintain political stability and security, improve infrastructure to boost economic growth, and improve economic governance in addition to offering more investment incentives.

Keywords: *Investment location selection, foreign direct investment, investment incentive policies, provincial competitiveness index, country risk index*

Classifying the shape of qPCR expression data

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Abstract: The application of real-time quantitative polymerase chain reaction (qPCR) methods for the identification and quantification of gene sequences requires automatic methods for the assessment of the resulting shape of the fluorescence readings. This requirement is especially important when we consider the use of rapid assessment hand-held qPCR devices, point of care operations and having to deal with a range of user expertise with qPCR interpretation. This paper describes a method for characterising different outputs from such devices by characterising the shape of the resulting fluorescence using a generalised sigmoid model based on the 5-parameter Richards function.

The shape of qPCR output should in theory follow a standard sigmoid shape, however with point of care devices with samples collected in the field there are a range of issues that may cause different responses. For example, biological samples can be contaminated, resulting in a reduced response for the PCR reaction, samples can have other chemicals that react with the amplification process, enzymes can be used that are not stable or have been destroyed due to heat or sunlight, and so on. Therefore a method is required to allow a range of output shapes to be classified, with an appropriate assessment for each type of output to then be presented to the user. In addition, qPCR devices have multiple wells for analysis with different behaviour. For example a well may be designed for a zero response, or have different DNA sequences, or use a specific concentration of DNA to confirm expected amplification to test that the device is working or for estimating DNA quantity. This means a flexible approach to assessing each well response is required.

This paper demonstrates the use of a simple one-dimensional line search algorithm for fitting the Richards equation, and the use of derived parameters from this model as input to a decision tree for shape analysis. The training data for shape analysis is created by adjusting the Richards parameters with associated noise. The advantage of designing different shapes by adjusting the parameters of the Richards equation is that unlimited training data can be sampled and automatically labelled for a specific shape. The use of appropriate noise levels ensures that the data is similar to real qPCR output. The resulting decision tree model demonstrates that a range of shape classes can be classified with high accuracy, and that the fitting of the parameters can be implemented without the use of complex matrix operations. The shape classification of the model to a range of test data of varying quality and fluorescence shapes is demonstrated on two real data sets created by different devices.

Keywords: *qPCR curve analysis, nonlinear optimization, decision tree, shape models*

Impact of positive and negative price shocks on investment portfolios in selected Asian markets

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Abstract: This study examines portfolios returns following markets large price movements and finds that large initial price increases are followed by price continuation and mixed stocks reactions to large initial price decreases. Despite the result suggesting that retail investors are unlikely to profit from such phenomenon after considering the relevant transaction costs, it is still possible for institutional investors to exploit the profit opportunities. In addition, the result shows that both bid-ask spread and market liquidity cannot explain the price reversal observed in this study.

Keywords: *China, index, spread, liquidity, portfolio, investment*

Pricing Carbon emissions for Japan based on energy production

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Abstract: Fossil fuels such as coal, oil and gas generate carbon emissions that contribute to global warming and climate change. Taxes on carbon emissions can mitigate their effects on the environment by changing demand and supply. For taxes to be effective, accurate carbon emissions prices are required. The paper uses an innovative KLEM production function approach to calculate carbon emissions prices for Japan, where carbon emissions are the output, and capital (K), labour (L), energy (E) (or electricity), and materials (M), are the inputs. The variables capital, labour and materials are essentially fixed on a daily, weekly or monthly basis, whereas energy can be changed more frequently, such as daily, weekly or monthly, so that changes in carbon emissions essentially depend on changes in energy. If prices are set according to average cost pricing, the prices of carbon emissions and energy may be approximated by an energy production model with a constant factor of proportionality, so that carbon emissions prices will depend on energy prices. Using this innovative approach, the paper estimates carbon emissions prices for Japan using seasonally adjusted and unadjusted monthly data on the volumes of carbon emissions and energy, and energy prices, from December 2008 to April 2018.

Keywords: *Fossil fuels, energy, carbon emissions, taxes, KLEM production function*

Modelling latent carbon emission prices: theory and practice

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Abstract: Climate change and global warming are significantly affected by carbon emissions that arise from the burning of fossil fuels, specifically coal, oil and gas. Accurate prices are essential for purposes of measuring, capturing, storing and trading in carbon emissions at the regional, national, and international levels, especially as carbon emissions can be taxed appropriately when the price is known and widely accepted. The paper uses a novel KLEM production function approach to calculate the latent carbon emission prices, where carbon emission is the output and capital (K), labour (L), energy (E) (or electricity), and materials (M), are the inputs into the production process. The variables K, L and M are essentially fixed on a daily or monthly basis, whereas E can be changed more frequently, such as daily or monthly, so that changes in carbon emissions depend on changes in E. If prices are assumed to depend on average cost pricing, the prices of carbon emissions and energy may be approximated by an energy production model with a constant factor of proportionality, so that carbon emission prices will be a function of energy prices. Using this novel modelling approach, the paper estimates carbon emission prices for Japan using seasonally adjusted and unadjusted monthly data on the volumes of carbon emissions and energy, as well as energy prices, from December 2008 to April 2018. The econometric models show that, as sources of electricity, the logarithms of coal and oil, though not LNG, are statistically significant in explaining the logarithm of carbon emissions, with oil being more significant than coal.

Keywords: *Latent carbon emission prices, fossil fuels, energy, KLEM production function, average cost pricing*

Contagion effect analysis of US to East Asia Stock Markets

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Abstract: The economy of East Asia countries depends on the US economy through international trade, international finance, and exchange rate policies. The objective of this paper is to investigate contagion effect between the East Asia stock markets and the US stock market by using the Markov Switching DCC-GJR GARCH model. The information about the contagion effect among the East Asia and USA stock market indexes was gathered daily during the period of July 1, 2009 to July 5, 2019, which was after the financial crisis. Since the dynamic condition correlation may shift because of regime switching, the conditional correlations were estimated by the application of Markov Switching DCC-Skew-GJR GARCH, which can be divided into high and low correlation regimes. The results showed that the conditional correlation is not constant with positive value. In addition, they can be separated into two regimes, including regime 1 with high conditional correlation (bear market), and regime 2 with low conditional correlation (bull market). The highest correlation could be observed between the USA and Japan Stock markets, followed by between the USA and China stock markets. Furthermore, the positive conditional correlations were found between the USA and other East Asia stock markets, and among East Asia stock markets themselves. This has concurred with the current situation when the effects of shocks such as the trade policy between China and USA not only created the impact between the two countries, but the impacts also spread to neighboring countries in East Asia. The contagion test results of this study confirms the occurrence of the contagion effect.

***Keywords**: Contagion, Markov-switching, Dynamic Conditional correlation, East Asia Stock Index, US Stock market*

Corporate social responsibility and the local dividend clientele effect

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Abstract: More than 50 years ago, Miller and Modigliani (1961) suggest a dividend clientele that investors have different preferences for dividends based on their ages and incomes. Graham and Kumar (2006) provide direct evidence for retail investor dividend clienteles by documenting that older and low-income investors prefer dividend paying stocks. Becker et al. (2011) argue that a higher fraction of senior residents who are 65 years old or older in a county generates a clientele that appreciate dividends more, causing firms in the same county to be more likely to pay dividends and pay higher dividends. Such an effect of local seniors, who are in the local area of a firm, on the firm dividend policy, namely the local dividend clientele effect, demonstrates a feedback effect of dividend clienteles on the firm managerial decisions. However, the motivation for firms to respond to the local seniors' demand for dividends remains a puzzle.

We conjecture that one motivation for firms to respond to the local seniors' demand for dividends comes from the firm's corporate social responsibility (CSR), more specifically, the firm's goodwill towards seniors in the community. Using a sample of 36,173 firm-year observations in the US during 1991-2016, we identify the impact of CSR on the local dividend clientele effect. In our baseline results, we find that in an average county with the fraction of local seniors equal to 0.123, a firm with an adjusted CSR score in the highest quartile is 1.9% more likely to pay dividends than its counterpart with an adjusted CSR score in the lowest three quartiles.

In robustness tests, we first conduct the matched sample analysis. We use the propensity score matching (PSM) method to create the matched sample. We regress the high adjusted CSR score dummy (*High Adj*), which is equal to one if the adjusted CSR score in a firm is in the highest quartile in a year, on the fraction of local seniors (*Local Seniors*) and control variables in a sample of firms with the adjusted CSR scores in the highest (treatment group) and the lowest two (control group) quartiles. Based on propensity scores, we create a one-to-one match for each observation in the treatment group without replacement. Second, we repeat our baseline regressions using alternative measures of dividends and CSR. We use *Yield*, the total dividend in the percentage of the market value, as an alternative for the dividend payment dummy (*Payer*) and use raw CSR score as an alternative for the adjusted CSR score. The positive relation between CSR and the local dividend clientele effect survives in all robustness tests, reassuring the impact of CSR on the local dividend clientele effect.

Keywords: *Corporate social responsibility (CSR), dividend clientele, local seniors, home bias*

Boardroom gender diversity and discretionary investment: The role of critical mass in the UK

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Abstract: There has been surge in promulgating the regulations on enhancing representation of female directors in boardrooms. In October 2011 the UK Financial Reporting Council (FRC) introduced regulations on promoting boardroom gender diversity in the UK Corporate Governance Code (UK CGC). Supporting Principle B.2 and B.2.4 focusses on firms to promote gender diversity by reporting gender diversity in its boardrooms and establishing a policy in achieving gender diversity in corporate boardrooms. The objective of these reforms is to enhance the monitoring capability of corporate boards and break the "old boy's network", which is expected to mitigate moral hazard problem and enhance firm transparency.

Despite the rising popularity of such regulations, the question remains, how effective are these in aligning managers-shareholders' interests? Inefficiency of investment in one of the problems arising as a result of lack of information transparency between managers and external capital providers. It leads to moral hazard and adverse selection problems, both of which lead to sub-optimal investments, resulting in hampering firm performance.

This study examines the association between boardroom gender diversity and quality of investments as measured by its discretionary component for the UK firms from 2006 to 2018. We document a significant and negative association between boardroom gender diversity and quality of investments. Moreover we find that all-male boards have the lowest investment quality while boards with 3 or more women directors have the highest investment quality. Also the boards with 3 or more female directors have a stronger and significant impact on enhancing investment quality, i.e. consistent to critical mass theory. Our findings are robust to alternative proxies of investment quality and boardroom gender diversity. We contribute to literature by providing evidence supporting critical mass theory. These findings contribute to the literature on ongoing regulatory debates on enhancing women representation on corporate boards.

Keywords: *Critical mass, investment quality, gender diversity*

Impacts of Microfinance Programs in Thailand

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Abstract: Thailand has been developing its economy based on national and social-development plans over the last six decades. These plans focus on economic growth by supporting the manufacturing industry in order to export products to other countries. As a result, the growth rate performance has been outstanding since the late 1950s. Moreover, the Thai economy had been one of the fastest-growing economies in the world, and the GDP grew 10 per cent per year in the 1990s (Warr, 2000). Poverty incidence has thus declined dramatically. However, income inequality is still a big problem in Thailand. TDRI (2004) and Bird, et al. (2011) suggest that microfinance can assist to reduce income inequality among the poor. Under the Thailand National Economic and Social Development Plan (NESDP), microfinance institutions (MFIs) are considered to play an important role to enable poor people to equally access financial resources and new financial products at reasonable cost (Tambunlertchai, 2015).

This paper evaluates the impacts of microfinance programs on economic and social welfare of households in Thailand. The study employs secondary data from the Socioeconomic Survey (cross-sectional data in 2017 and panel data in 2012 and 2017) to evaluate the impact of the MFIs. The estimation methods include propensity score matching (PSM) and a fixed effect (FE) model.

The result shows the impacts of Village Funds (VFs) are significant in terms of income and expenditure but not on housing, food, and medical expenditures. However, the impacts of VFs are negative. In terms of Saving Groups for Production (SGPs), the empirical results reveal that SGPs effects are significant in income but insignificant in expenditure. The FE model result also shows that VF impacts only education expenditure, but impacts on income and transport expenditure of SGPs.

Keywords: *Poverty, Microfinance institutions, Village Funds, Saving Groups*

Risk tolerance, investment horizons and debt decisions

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Abstract: Formal and informal debt play an important role in investors' choices. The literature on investors' use of debt is, however, limited. In particular, the impact of risk tolerance and investment horizons on debt decisions has been unexplored.

Vietnam is uniquely useful as informal borrowing is common in Vietnamese culture. Using data of 420 individual investors, we find a direct impact of (i) risk tolerance and short horizons on financial leverage, (ii) preference for short-term over long-term stock investment (SHOLO) on investment risk tolerance and informal debt, and (iii) long horizons on informal debt. SHOLO indirectly linked investment risk tolerance and informal debt. Investment risk tolerance linked SHOLO to financial leverage. These results are robust after controlling for demographics and using additional techniques.

The implications are that individual investors should consider the degree of risk tolerance when making decisions on investment horizons and borrowings because the higher the levels of risk tolerance, the higher is the preference for a short trading horizon, and the higher the preference for financial leverage. Both the preference for short-term over long-term stock investment and long horizons cause risk-tolerant investors to use high informal debt. Additionally, investors' attention needs to be drawn to the fact that if their stock investment fails, all lenders may be severely affected.

Keywords: *Debt decisions, financial leverage, informal debt, investment horizons, long-term investment*

Credit and non-credit support services on rural household welfare in Thailand

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Abstract: Several studies have documented that microcredit is not successful in promoting rural household welfare. In order to improve the effectiveness of credit, some researchers suggest that non-credit support services could be provided simultaneously with credit. In spite of Thai agricultural cooperatives (ACs) providing credit and non-credit support programs to help the rural households, the numbers of poor in rural areas have not been reduced significantly as forecasted. Using the Endogenous Switching Regression and Endogenous Switching Probit models, this study examines the effects of AC credit and non-credit support services on Thailand rural household economic and social welfare. The data is collected in 2017 using a household survey questionnaire from AC members and non-members. The survey is administered to rural households in the Nakhonratchasima province, in Northeast Thailand. A two-stage stratified sampling technique is used to select rural household sample from the study population. The first stage involves selecting one district from each area which has the greatest number of AC members. The second stage involves section of household selection from each district. The disproportionate stratified random sampling method is used to determine the sample size of each district.

The results show AC services play important roles in improving household economic welfare. AC credit exhibits significant positive effects on household and farm income, and household consumption. AC marketing service participation increases household and farm income but not consumption. Interestingly, AC credit and marketing services do not improve children's education in terms of educational expenses and school enrolment rates. Only AC credit considerably increases the adoption of improved farm technologies and practices, however, using AC agricultural extension services does not improve farm production. Regarding health effects, households' health affordability and health access improve when they borrow money from, or trade with, ACs. Finally, AC credit and marketing services indicates that AC marketing service is more effective in improving household welfare in terms of household and farm income, consumption, health affordability, and healthcare access improvement.

Keywords: *Credit, non-credit support services, agricultural cooperatives, endogenous switching regression model, endogenous switching probit model*

Petty corruption on firm level innovation of MSMEs: Evidence from emerging economies

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Abstract: In this study, we examine how petty corruption affects micro, small and medium firms (MSMEs)'s innovation in emerging economies. Innovators from emerging economies face considerably high bribing pressure from corrupt public officials and no or little institutional support for innovative firms (Kotabe, Jiang, & Murray, 2017). Corruption undermines the foundations of institutional trust, which is necessary to develop entrepreneurial and innovative activities. It has been argued that corruption increases transaction costs, which makes innovative opportunity much less attractive. Since innovators have been recognised as the main driver of long-term economic growth, a clear understanding of how corruption affects innovation can assist the MSMEs development.

Our examination of the relationship between innovation and corruption uses firm-level data for 3368 MSMEs in South American countries. We observe some firms that pay bribes and others that do not, but a direct comparison between them leads to an identification problem because the engagement with bribery may correlate with unobserved determinants of firms. To overcome this potential bias, we use propensity score matching (PSM) to find a comparison group for individual firms in the bribe-paying group. After controlling for firm characteristics and taking care of firms' observable characteristics typically linked to innovation decisions, we find systematic differences in firm-level innovation activities associated with paying bribes. In particular, results indicate that the estimated average effect of paying bribes on innovation outcome for firms who engaged in bribery is 11 percent. However, significant heterogeneity in innovation and paying bribes is also observable. Empirically, we find that the average effect of paying bribes on innovations is significantly higher on process innovation outcome than product innovation. We also observe that with weaker institutions, the effects of bribery on innovation is more pronounced. The main knowledge contribution of this paper is twofold. First, to the best of our knowledge, this paper is the first investigation of innovation in MSMEs from the perspective of innovation and corruption, using cross country micro-data, which are rich and recent. Also, extending prior research, we further report a heterogeneity effect of paying bribes on product and process innovations. Prior innovation studies, which use micro-data, mainly examine a single country Comparative studies using micro-data focus on large firms in developed markets.Policy derived from these large firm and mature market studies seems problematic for MSMEs in emerging economies, given the size effects, corruption levels etc. Second, this study provides a fresh perspective to that of previous studies of corruption in emerging economies, highlighting the importance of formal institutions in dealing with corruption. While prior studies on the role of institutions has focused on mianly formal tension (Cuervo-Cazurra, 2006, 2008), this study emphasizes the importance of the local environment in gaining legitimacy in the role of innovative entrepreneurs or MSMEs. In emerging economies, ineffective legal enforcement of contracts, weak regulations, and difficulty in enforcing property rights encourages private entrepreneurs to rely on informal forms of security (Ahlstrom, Bruton, & Lui, 2000). Consequently, informal ties and relational governance tend to fill the 'institutional void' where there is inadequate formal institutional infrastructure

Keywords: *Corruption, innovation, bribes, MSMEs, credit access, emerging countries*

Short term forecasting of solar farm output

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Abstract: In Australia, every five minutes throughout the year, scheduled generators are required to submit a bid stack, detailing the amount of energy they can supply in the next five minutes at ten price levels in the stack. Semi-scheduled generators such as wind and solar farms about 40 MW submit their expected output in that time period, but they are price takers so they do not delineate prices in ten bands. They are also in a special category in that they can be ordered to curtail production if there is too much supply. After the bids are entered, AEMO runs a linear program to see how far up the bid stacks they have to go to meet their forecasted demand. The price that is reached is thus the five minute price. Every half hour the six five minute prices are averaged to determine the spot price for all electricity supplied during that time and the market is cleared. The forecasting of wind, and more recently solar, farm output on the five minute to one hour time scale has proven problematic for AEMO, since the tools that they have used have been deriving them from longer term forecasts using such methods as numerical weather prediction (NWP). As a result, ARENA set up a grant scheme to have better methods developed. Various consortia have been funded under these scheme to enhance the performance of the forecasting, and each team must include a variety of wind or solar farms or both. So, this research is funded by the Australian Renewable Energy Agency (ARENA) under the project **Solar Power Ensemble Forecaster**.

Statistical forecasting of solar farm output

In Australia, as of September 2018, there were 20 solar farms of 50 MW or more, with the largest being 220 MW. And there are a large number of farms under construction and many more in the planning stages. This means that robust forecasting tools are urgently required. The author, along with co-workers, has developed so-phisticated statistical forecasting tools for solar energy, specifically global horizontal irradiation (GHI). There are significant differences between forecasting GHI and output from solar farms in Australia. This is typified by and examination of the type of profile on a clear day for the two situations. The GHI shows a distinct peak in the profile. On the other hand, the solar farm output profile is, on a clear day, flattened at the peak. As to specifically why this is, one can speculate. The most obvious answer is that the seeing the panels are now very inexpensive, it is advantageous to oversize the field of panels and through having smaller capacity transfer equipment, limit the output so that it is easier to know the maximum output and for operational purposes keep to that value throughout a few hours of a clear day. This paper will describe both the point forecasting and probabilistic forecasting methods for solar farm output given these constraints. It is necessary to adjust the previous tools to suit this particular alteration.

The approach taken previously includes:

- Identify the seasonality of the irradiation using some years of data as a training set.
- Formulate the model for seasonality using Fourier series, and then subtract that model from the data.
- Take the deseasoned data and construct an $ARMA(p, q)$ model for it.
- Use the combination of the two to set up a one step ahead forecast tool.
- Apply the model to the test set of data and evaluate the performance versus other approaches.

The alterations in this case are somewhat simple in the first instance. Since the output is capped for most of the farms we will consider, when we get the forecast value, we check to see if it exceeds the cap, and if so, reduce the forecast value to equal the cap. In the present project, this approach will be coupled with the sky camera and satellite image forecasting tools as a blended forecast to improve the skill.

Keywords: *Solar farm, forecasting, clear sky output index, autocorrelative effects*

Forecasting irrigation electricity demand using a machine learning model

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Abstract: As with any other country, electricity demand in New Zealand is highly variable within and between days due weather and a range of electricity demands that can coincide (e.g. residential, commercial, and agricultural). This variation in demand can result high peak electricity demands and necessitate new infrastructure to support these peaks. In some regions, the peak demands can also result in annual allocations of national grid transmission costs to the region that fluctuate widely. For example, for the last four years EA Networks (EAN) in the Ashburton supply area (Mid-Canterbury) have to pay M$3.8, 9.0, 4.2 and 14.5 as their share of the national grid costs. Analysis of EAN peaks causing the fluctuation in charging has shown that they generally coincide with prolonged heat and/or little rainfall during late spring and summer when irrigation demand is high. If these peaks could be accurately predicted and irrigation timing phased to avoid the peaks, then these extra transmission costs might be avoided.

We investigated a practical solution to predict high electricity demand by irrigators based on weather and soil moisture and prior electricity consumption. The electricity consumption data was provided on an anonymised basis by an electricity provider that supplies a number of irrigators in the district. In this initial investigation, we used the actual weather with some random noise added rather than forecast weather – acknowledging that eventually replacing this with forecast weather will likely degrade performance of the predictions. We used the eXtreme Gradient Boosting (XGboost) algorithm to train the model for data up to Aug-2017 and then iteratively re-trained the model dynamically every day. The model was offered many electricity, weather, soil, and calendar variables and was able to predict *Next-day* electricity demand (Figure 1). *Previous-day* electricity demand was the most important predictor along with weather (*Radiation*, *Wind speed*, *Rainfall* and *Temperature*). *Day-of-week* and *Month* added minor predictive ability. For *Month*, this is to be expected as other weather and soil moisture variables most likely absorbed seasonal effects which would affect irrigation usage. Future development of the model will include incorporating forecast (rather than actual) weather variables, longer prediction horizons (e.g. 2 to 7 days). We are coupling this with dynamic soil-crop system modelling to understand the potential impacts of not irrigating to manage electricity demand at peak times. In the future we will also combine this electricity forecast model with a multi-agent simulation to represent a diversity of farms with varying physical (e.g. soil, weather, irrigation, on-farm sensors), farmer 'personas' (e.g. sensitivity to loss of production or profit, affiliation for data, connectedness, …) and peak electricity tariffs to explore the likely impact of these factors on electricity demand.

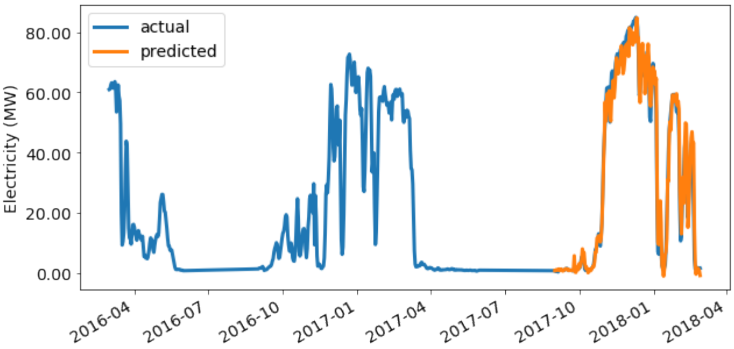

Figure 1. Actual (blue) and predicted (orange) daily electricity demand for irrigation.

The model can predict electricity demand for the next day with a high degree of accuracy using current day electricity demand, and a combination of weather and soil variables. Further development is required to consider additional seasons of electricity data, forecast weather, longer term prediction horizons, and to explore the impact of communicating peak electricity forecast predictions and tariffs on farm behaviour change.

Keywords: *Irrigation, electricity demand forecasting, machine learning*

Time-space dependency of utility-scale solar photovoltaic power generation in the National Electricity Market

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Abstract: Driven by declining costs and the Large-scale Renewable Energy Target (LRET) in particular in Australia, the installation of utility-scale solar photovoltaic power is rapidly increasing in the recent few years. Consequently, accurate solar power forecasts are urgently needed to efficiently and economically integrate variable solar power generation into the inter-connected power system and to ensure national energy security. In addition to a central point power forecast, the associated uncertainty information is more and more being regarded useful to inform critical decision making such as planning for contingency events. As such, probabilistic forecasting of solar irradiance or power is receiving more and more attention from solar energy researchers.

Most probabilistic methods forecast solar irradiance or power at specific time and location independently without explicitly treating time-space dependency of scattered solar power generators. This is fine as far as individual solar power generators and independent time periods are concerned. However, under scenarios where the aggregated power in time and space is most concerned such as supply-demand balancing for inter-connected power systems, the time-space correlation of solar power generation will likely play a role and thus an explicit treatment of its time-space dependency becomes important. In this study, we investigate the power output of four adjacent utility-scale solar farms which are connected to the National Electricity Market using gaussian copula. We have quantitatively demonstrated the benefit of retaining the time-space dependency in probabilistic forecasting of solar power.

Keywords: *Time-space dependency, solar forecasting, probabilistic forecasting, gaussian copula, quantile regression*

Improving solar power forecasting to reduce regulation Frequency Control Ancillary Services causer pay in the National Electricity Market

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Abstract: Driven by many factors including sharply declining costs and the pressing need for climate change mitigation, in particular the Large-scale Renewable Energy Target (LRET) in Australia, the installation of renewable energy generation such as wind and solar is rapidly increasing all over the world. Since 2015, more and more utility-scale (>30 MWp) solar farms are being commissioned and connected to Australia's National Energy Market (NEM). However, the power generation from wind and solar resources relies on complex weather and climate processes and is inherently variable. Together with other uncertainties such as load forecasting errors, this could result in generation-load imbalance, which in turn causes fluctuations of AC frequencies in the grid.

Since all electric equipment connected to the grid (e.g. household appliances and steam turbines) is designed to operate at or close to 50 Hz in Australia, frequency control is critically important to maintaining a secure and reliable power system. To address this issue, the Australian Energy Market Operator (AEMO) frequently corrects the generation-load imbalance via a 4-second market mechanism to restore system frequency back to the nominal 50 Hz through the procurement of regulating Frequency Control Ancillary Services (FCAS). Cost for this market are recovered under a mechanism known as 'causer pays', whereby a grid-connected solar farm is liable for the part of costs according to its estimated contribution to the need for regulating the grid frequency. However, although it is widely recognised that the quality of power forecasts of renewable generators relates to the need (hence the associated costs) for frequency regulation to some extent, a quantitative model of the relationship remains unavailable.

In this study, we use high-temporal-resolution generation and forecast data published by the AEMO to reveal the functional relationship between causer-pay contribution factors which are proportional to actual payments assigned to individual solar farms and the quality of solar power forecasts issued by the Australian Solar Energy Forecasting System (ASEFS). We found that the contribution factors are largely due to the coincidence of a positive forecasting bias and a low system frequency. We then manage to effectively model the contribution factor of a solar farm using information only for that solar farm.

Keywords: *Solar forecasting, frequency control ancillary services, causer pays, regulation service, mean absolute error*

Prediction of traffic demand using deep generative adversarial neural networks

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Abstract: Transportation plays a key role in societies. The transportation system of a country is closely related to development of its economy by meeting travel demand of people and allowing the transport and the exchange of resources. Nevertheless, transportation is also endowed with negatives effects: growth of transportation demand can lead to an increase of accidents, environmental issues such as air and noise pollution, and energy consumption. Understanding and forecasting the dynamics of transportation system has then naturally become a major research field. The computer assisted transport simulation has a long history since beginning in 1955.

Recently, the advent of advanced machine learning such as deep neural networks has paved the ways towards new methods to predict the traffic dynamics in and between cities. In particular generative adversarial networks is one of the most promising recent developments in deep learning to generate realistic outputs. In addition, recurrent neural network such as long short-term memory neural networks are able to reproduce dynamic temporal behaviour.

In this research, we investigate the feasibility of using a recurrent deep convolutional neural network trained with generative adversarial learning to estimate the traffic dynamics in a given road network. Despite its successful application in many other areas, this framework has yet to be tested in the context of traffic demand estimation.

This work thus presents a proof-of-concept model aiming to predict the level of traffic on the road network given its topology (road type, number of intersections, …) and the land use (e.g. residential, urban, industrial, commercial, parks, agricultural, …) in its surroundings. The interaction between land-use and the road network is crucial to accurately estimate the traffic flows on the network. This data can be difficult to collect, but can be easily approximated by extracting snapshots from online map services such as Google Maps and Google Traffic. The extracted data can be used to train a machine learning algorithm such as a deep neural network trained to estimate the traffic based on the initial map. This process is illustrated in Figure 1.

Having this initial model allow us to gather preliminary results and explore the potential of the proposed approach. This represents an important step towards the design of a tool for city planners which will be able to predict and optimise transportation in cities, suburbs, villages and new development.

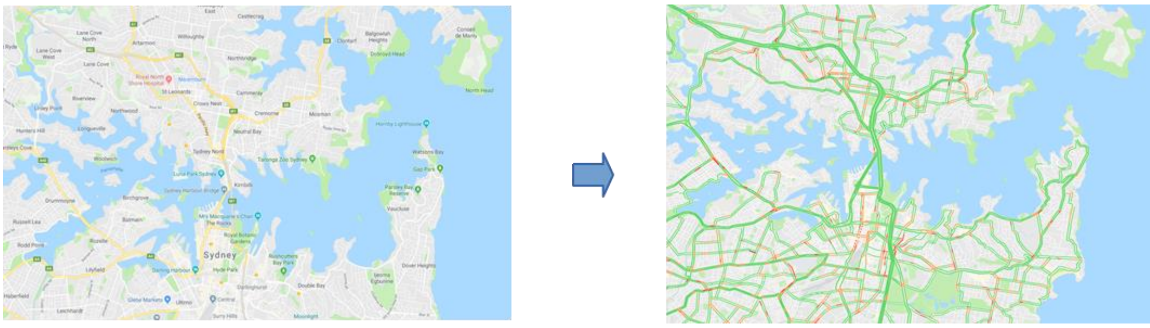

Figure 1. From an image extracted from Google Maps to traffic prediction.

Keywords: *Traffic prediction, deep generative adversarial neural networks, GAN*

Traffic simulation using real-time smart sensor data: The case of Liverpool

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Abstract: Complex systems, such as social networks, the brain, financial systems, infrastructure and road networks are composed of a large number of entities in interaction and exhibiting emerging dynamics. The ability to reconstruct the temporal dynamic of a network is an important research topic with many applications, but also often limited by the amount of information available.

In the context of a road network, the dynamic is defined by the amount of traffic flowing through its links (or road) and nodes (intersection) at any moment *t*. Typically, the data available to reconstruct traffic flows is either gathered manually by observers or automatically by monitoring devices along the roads of interest. However, it is nowadays possible to use the next-generation of smart visual sensors, using edge-computing solutions to monitor traffic. These new sensors are capable of tracking and automatically differentiating various types of traffic components such as cars, buses, bicycles or pedestrians in real-time. The processed data is then transmitted to a centralized database and can be visualized on a dashboard in real-time. Such system has been deployed successfully in Liverpool (NSW, Australia) in 2019 and illustrated in Figure 1.

Figure 1. Location of visual sensors in Liverpool.

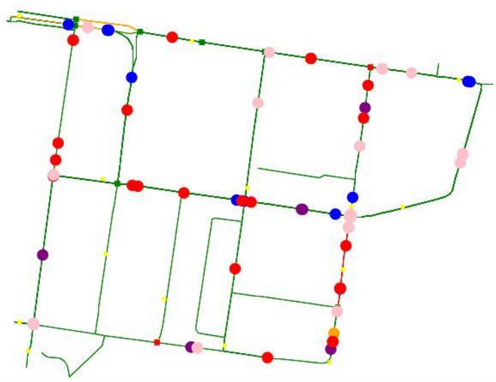

Figure 2. Agents travelling in the road network.

This exploratory works aims at demonstrating the feasibility of developing an agent-based simulation to infer in real-time the dynamics of the traffic flows in a road network based on localized sensor data. The implementation relies on the GAMA platform, a free and open agent-based framework with a strong focus on spatial simulations. The model receives in real-time data from the sensors which is used to generate origin-destination matrices to estimate the demand on the network. The origins and destinations correspond to the sensors' locations in the network which will be thus acting as generator of travelling agents and attractors for those agents. A newly generated agent will then compute a path to a randomly selected destination. The random draw is weighted against the traffic count observed by the sensors. It should be noted that a travelling agent can represent either a pedestrian, a bicycle or a vehicle as the smart visual sensor is able to detect and differentiate those three types of entities.

The proposed approach will not only deliver a novel methodology to accurately monitor and predict different type of traffic flows in cities, but will also be applicable to many other situations where the structure of the network and some partial information is known, but the dynamics are still unknown

Keywords: *Traffic simulation, agent-based modelling, data-driven simulation*

An agent-based approach for flash flood prediction and prevention in Wollongong (NSW, Australia)

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Abstract: Flooding is one of the most frequent natural disaster, accounting for up to 50% of the disasters in 2014. It is also one of the most damaging and costly disaster. On average, floods affect the life of more than 60 millions people yearly. These events are occurring more frequently due to global warming as sea levels are rising and severe meteorological events become more frequent and extreme. Flood can be caused by many different factors and phenomena, nonetheless this research focuses on the floods due to heavy rainfalls in the Illawarra-Shoalhaven region.

Indeed, over the past 50 years the Illawarra-Shoalhaven region has experienced 30 floods classified as serious, severe or very severe and three classifieds as extreme. The *Illawarra-Shoalhaven Smart Water Management Project* aims to offer a solution to that flooding issue by using new smart remote sensing technologies coupled with agent-based models and data analytics to help improve water quality, flood mitigation and ensure community safety in flash flood events. The project is delivered through five components:

- *Stop Block:* Improved stormwater culvert blockage management and analytics including new rugged sensors;
- *Go Flow:* New estuary management solutions including sensors and cameras to reduce flooding;
- *Quality Watch:* New water quality monitoring stations including custom technology, sensors and a regional Internet-of-Things network;
- *Pollution Stop:* Improved management of gross pollution traps with new sensing devices and analytics allowing real-time monitoring of this infrastructure;
- *Flood Aware:* an agent-based hydrological model using data from the other components to predict flash flooding events. The model introduced in the work will be at the core of this component.

The classical approach for flood prediction relies on the use hydrological models and computer-based simulations dividing the study area in predefined catchments and stream networks. Thus, this approach requires a large amount of accurate data and does not allow the simulated water runoffs to flow outside the given stream network.

The approach proposed in *Flood Aware* relies on a cellular automata approach for model the runoffs. Using this paradigm, the catchment is divided into a grid where each cell is an autonomous agent. Each agent is connected to its neighbours in order to simulate the runoffs during a rainfall event. Even though the development of this approach is still in its early stage, it is clear that its main advantage is its capability to easily highlights all the potential flooded area, even the ones that were not explicitly specified by the modeller. The models only requires shapefiles detailing the area of interest (geography, buildings, infrastructures, …) and most importantly an raster file detailing the elevation of the area. This model, illustrated in Figure 1, is developed using the GAMA platform, a free and open-source agent-based framework for spatial simulations.

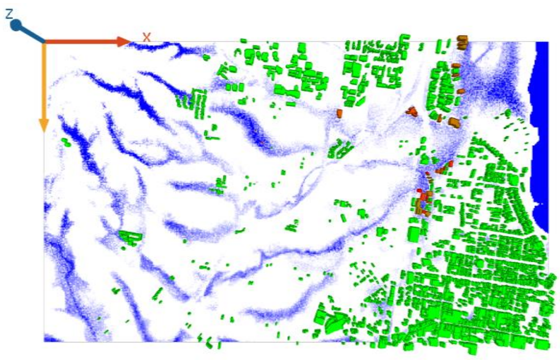

Figure 1. Output of the GAMA model for the Wollongong area. The water and runoffs are in blue. Damaged buildings are in red. Preserved are in green.

Keywords: *Agent-based modelling, hydrology, flash flood*

Using IoT data to derive enhanced predictions of CO_2 emissions

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Abstract: The rapid growth of IoT devices has started people thinking about how to incorporate these data into models of economic, social and demographic processes. There are risks in terms of the quantity of data feeding into the model, and the potential quality of the data. There has been some research on reducing the quantity of data using the “four principles of orderly loss of information”, and some on the quality of IoT data.

This paper uses IoT data from a study in Queanbeyan, NSW. There was extensive amounts of data collected from a number of devices, but this paper looks at CO2 emissions, and models predicting the time and extent of CO2 emissions. We look at the quality of the data being produced by comparing it over time and space, and then look at how data could be reduced by applying the four principles of orderly loss of information. These four principles are:

1. Expansive inclusion: at the outset of each project, every possible data element is included. Any loss of data is therefore due to analytical decision making and not by prior omission.

2. Iterative loss: in order that key trends and spatial structures can be identified, the process of analysis with spatial interaction data proceeds via several stages of repetitive experimentation, whereby the important elements are made visible and the background `noise' eliminated.

3. Simplicity from complexity: this principle is very much related to the skill of individual analysts and relates to the degree to which very complex spatial interaction datasets can be rendered intelligible.

4. Optimal compromise: each of the previous three principles can be situated within a framework of `optimal compromise', since geovisualisation attempts to maximise the effectiveness of visual communication, whilst minimising the impact of what is not displayed. (Rae, 2009)

We look apply these rules to our large dataset, while also refining them in light of the large amounts of data coming into our system, the need for continual assessment of this data, and the final use of this data in a prediction model. We then use the cleaned and non-cleaned data to derive predictions from each device for each day and hour to provide a baseline prediction without data cleaning, a prediction with data cleaning, and then a prediction based on a moving average of the latest records (both cleaned and uncleaned). An autoregressive model using the cleaned data is also tested to enhance the predictive power of the model due to the expected autocorrelation over time in CO2 emissions.

Keywords: *Integrated modelling, integrated assessment frameworks, conceptual model*

The application of evolutionary computation and metaheuristics for solving the Network Design Problems

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Abstract: Network Design Problems (NDPs) can model many real-life problems in a wide range of domains from transportation, supply chain management and logistics, through to the design of telecommunication networks and airline routes. NDPs are generally tackled through employing sophisticated exact methods and (meta-)heuristics. Exact methods mainly include mixed integer programming, column generation, and branch and bound techniques. Metaheuristics, as the second strategy of solving NDPs, can comprise any construction methods, local searches (point-based), evolutionary (population-based) techniques as well as their hybrids. In this abstract, we discuss the challenges and potentials of designing an effective hybrid metaheuristic for solving NDPs by considering the Steiner tree problem as a representative for NDPs.

The Steiner tree problem can be considered as a generalised minimum spanning tree problem. Whilst the objective of minimum spanning tree problems is to find the minimum-total-weight subset of edges that connects *all* the nodes, the Steiner tree problem is not constrained to include all the nodes. It still has the same objective but only requires a *subset* of nodes, called *terminals,* to be connected and the rest of nodes are optional for being included. This simple relaxation makes the problem highly intractable (NP-Hard). Such relaxation of constraints makes the design of a hybrid metaheuristic a valid alternative for this very interesting problem.

Metaheuristics applied to Steiner tree problem can be categorized into construction methods, point-based methods and local searches as well as population-based and evolutionary methods. Whereas construction methods incrementally create a solution in each iteration, point-based methods start with a complete solution and they then traverse the search space by moving from one solution to another in each iteration, aiming to improve the solution quality. In effect, population-based techniques enhance the solution quality by operating on a pool of complete solutions, employing the notions of *competition* (via selection) and *co-operation* (via genetic recombination).

The key to proposing an effective general metaheuristic the Steiner tree problem is a synergistic combination of the aforementioned techniques, aiming to strike a balance between *intensification* and *diversification* aspects of the search process (Figure 1). Analysing the fitness landscape of the problem in question is also of high importance in this regard.

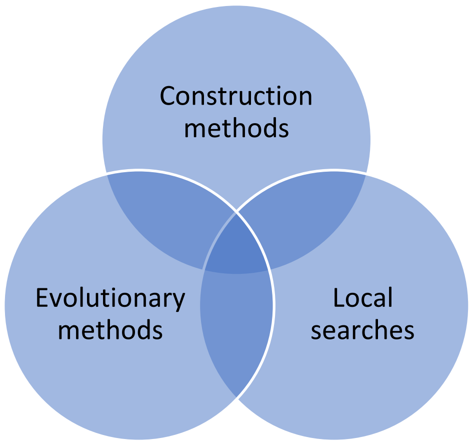

Figure 1. A synergistic hybrid of three search strategies

Keywords: *Network Design Problem, evolutionary computation, metaheuristics, minimum spanning tree, Steiner tree problem*

Ensuring robustness in the Stochastic Capacitated Vehicle Routing Problem: A new mathematical model

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Abstract: As researchers attempted to better represent real-life routing problems faced by companies, uncertainty was incorporated in the classical Capacitated Vehicle Routing Problem (CVRP) by modeling the uncertain input as a stochastic variable, giving rise to the Stochastic CVRP (SCVRP). The SCVRP can be studied from two perspectives: static and dynamic. While from a static perspective the aim is to calculate a priori robust route plan that will go through small changes (recourse actions) during its implementation, from the dynamic perspective the goal is to design a solution in an ongoing fashion by communicating to the vehicles which customer to serve next as soon as it becomes idle. Although the ability to modify a route plan allows for additional savings, this ability is limited as a result of the availability of technical support, time of the information disclosure, and the amount of work in computing new solutions. Holding a robust solution, i.e. a route plan that is relatively insensitive to fluctuation on the demands, has practical advantages as it can conduct to better training of drivers who become accustomed with a region or plan and are, thus, more capable of managing unforeseen situations and/or emergencies. Nevertheless, imposing protection by creating solutions that are robust conducts to the so-called *Price of Robustness*. This price is defined as the cost one has to pay in order to be safe against perturbations in the stochastic input. A solution will hardly remain both robust and optimal for all realization of the uncertainty. Hence, there exists a tradeoff between optimality and robustness.

In this work, we propose a mathematical formulation for SCVRP with stochastic demands based on the Mean-Variance (MV) objective function. This objective function combines two conflicting objectives, minimization of the mean of the total distance (optimality) and minimization of the variance of the total distance (robustness) into a scalar one. In the MV model, the variability term is multiplied by a parameter of decision-maker's choice, used to obtain a spectrum of route plans that can be more or less robust. In this manner, the proposed formulation not only delivers flexibility to the logistics manager to define desired level of robustness, but also allows to trade off cost minimization and protection against fluctuation in the uncertain demands.

We compare the robust solutions with solutions designed via a benchmark modeling approach. A common and simple modeling approach for the SCVRP is to model it as the deterministic (classical) CVRP. By doing this, one instance of the demands is fed to the Integer Linear Programming (ILP) model. In this instance, the stochastic demands are set equal to their expected values. For solving both ILP and MV models we used a solution method that consists of three heuristics, namely Clarke and Wright (C&W), 2-Opt Local Search and Simulated Annealing (SA). We selected four performance measures that have been used in the literature, planned and simulated total distance, planned and simulated number of routes, and the *Price of Robustness*. Planned total distance and number of routes and the Price of Robustness are characteristics inherited by a route plan. On the other hand, Monte Carlo simulation was used to estimate simulated total distance and number of routes. Using the MV model the final route plan can only be known after all demands are revealed. Thus, if the real demands are simulated, the final total distance and number of routes can be estimated. By simulating the demands, we can infer how many times a route failure happens and how often recourse actions were implemented. A detour-to-depot is adopted as the recourse action, i.e. if a failure occurs, a detour-to-depot is applied and an extra route arises. Simulated total distance is then equal to planned total distance plus recourse distances, and simulated number of routes is the sum of planned and extra number of routes. We also use the proposed model to solve a real-life problem, a selective waste collection system in Brazil. The tradeoff between optimality and robustness of solutions to this problem are analyzed.

The comparison between MV solutions and solutions calculated via benchmark approach shows that the proposed model designed route plans that are more robust, that is MV solutions were less sensitive to uncertain demands than ILP solutions, incurring in fewer route failures and recourse actions and consequently shorter recourse distances. Nevertheless, the price payed for this safety was high. Moreover, the parametrized MV formulation was able to design a solution for the selective waste collection system that calculates a good tradeoff between optimality and robustness, i.e. a route plan of lowest real total distance.

Keywords: *Vehicle Routing Problem, robustness, stochastic demands*

Measuring the perceived leasing price of empty container in shipping system

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Abstract: The container shipping activity has increased significantly with the growth of world economy and global trade. However, due to the imbalance of global trade, there is always an imbalance between import and export containers, which results in that some ports have a surplus of empty containers while the others have a deficit. At a surplus port, storage cost and repositioning cost for shipping companies increase inevitably; while at a deficit port, shipping companies have to lease or purchase empty containers to meet customers' demand. Empty container repositioning is one of the most effective ways to solve such imbalance problem, however the repositioning cost has increased from $11 billion in 2003 to $16 billion in 2012. To reduce the related expense for container repositioning, a significant body of studies have been done on container fleet management, and most of them considered the price of leasing empty container given as input parameters. However, leasing price plays an important role as a variable in the decision of container leasing activities by shipping companies.

Container leasing was often ignored to simplify the models, and to our best knowledge, only a few researches have measured the perceived container leasing price considering owned containers or long-term leasing only. Moreover, the process of delivering containers to consignors and consignees was often ignored. To fill in the gap, this study aims to measure the time-varying perceived leasing-in price taking both long-term and short-term leasing activities into account. It is assumed that long-term leased-in container will be treated as owned container and for short-term leasing, and containers would be returned to lessor at designated port after emptied.

The process of measuring the perceived leasing prices is described in terms of the formulation of models, as shown in Figure 1. Firstly, considering the turn-around time of containers in inland transportation, a model with the objective to minimize the relevant cost for empty container repositioning and cargo routing is formulated. The constraints ensure leased-in empty containers and laden containers must be transported to the destination and describe the flow balancing of containers on vessels and the change of empty container inventory at ports. Based on the initial model, the solution without leasing activities can be obtained and its dual model can be derived. It is assumed that the original leasing price is sufficiently small negative so that by following inverse optimization technique the objective of inverse optimization model can be described as minimizing the adjustments of original leasing prices to make the solution without leasing activities be the optimal solution. Then according to the primal-dual complementary slackness conditions, the inverse optimization model for measuring the perceived leasing prices is built. Based on the solution of inverse optimization model, for liner carriers, it is economic to lease in empty containers when realistic leasing price is lower than perceived leasing prices and it is better to reposition empty containers when realistic leasing price is higher.

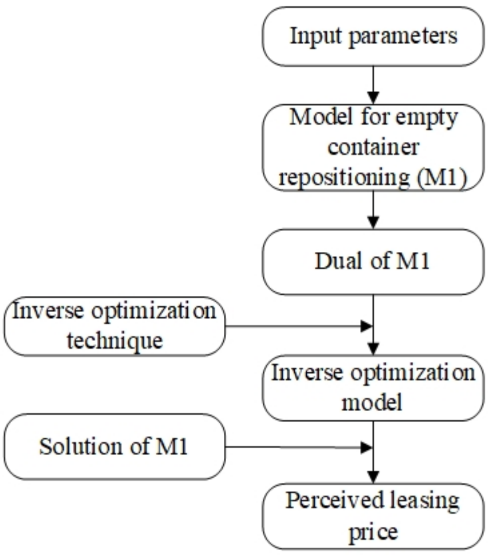

Figure 1. The process of measuring the perceived leasing prices

A real-world shipping network with four routes connecting Asia and West Coast of North America was employed to measure the perceived leasing price. By comparing the perceived short-term prices between ports along different routes, we found that the perceived leasing price at a deficit port was various for different routes and it was related to the schedule of vessels deployed along the routes. Compared to the fixed perceived leasing price, time-varying perceived leasing price was more practical since it changed with the inventories at both original and designated ports.

Keywords: *Empty container repositioning, perceived leasing price, inverse optimization*

A comprehensive simulation platform for conventional, connected and automated driving

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Abstract: The emerging connected and automated driving (CAD) is paving the way towards the higher level of trans-port automation and fundamentally transforming the modern transportation. A comprehensive assessment of CAD is imperative before its large-scale deployment in reality, which can be economically and effectively implemented via a credible simulation platform.

Nonetheless, the key components of traffic simulation, vehicle modelling and traffic environment, are over-simplified in the existing simulators. Firstly, current traffic simulators normally simplify the function of con-nected and autonomous (CA) vehicles by proposing incremental improvements to the conventional traffic flow modelling methods, which cannot reflect characteristics of the realistic CA vehicles, especially in terms of intelligent perceptions and control decisions. Secondly, typical autonomous vehicle simulators only focus on individual function verification in some specific traffic scenarios, omitting the network-level evaluation that integrates both large-scale traffic networks and V2X (i.e., vehicle to anything) communication. Thirdly, traffic dynamics generated by traditional simulators even cannot realistically reflect dynamics of the real world traffic due to lacking sufficient field test data and effective models to reliably approximate human driving behaviour. For example, geometric features, such as road surface and gradient, which may significantly affect driving behaviour, have not been fully considered in current car-following models.

This paper aims to build up a complete simulation platform for CAD from a transportation cyber-physical system perspective, which includes the core components of V2X communication, traffic networks, and autonomous/conventional vehicle model. Specifically, the simulator Webots is adopted to simulate connected and autonomous vehicles, which can easily functionalise the core components of a typical CA vehicle including Lidars, cameras, powertrain, and the implementation of common AI algorithms. To build up a 3D traffic environment, the elevation information from the external resource (e.g. Nasa SRTM) is added to OpenStreetMap data, which then are imported to Webots to create a CAD environment using OpenStreetMap Importer. To extend CAD simulation from the individual level to the network level, the traffic simulator SUMO will be integrated with Webots which can flexibly build up large-scale traffic networks with different traffic conditions. OMNeT++ is selected as the module of vehicular communication to construct a connected environment, which supports popular V2X communication protocols such as IEEE 802.11p and LTE-V2X. All of the three modules can be connected via the Traffic Control Interface (TRACI), a TCP based client/server architecture, and run in parallel, wherein SUMO acts as the server and OMNET and Webots serve as the clients.

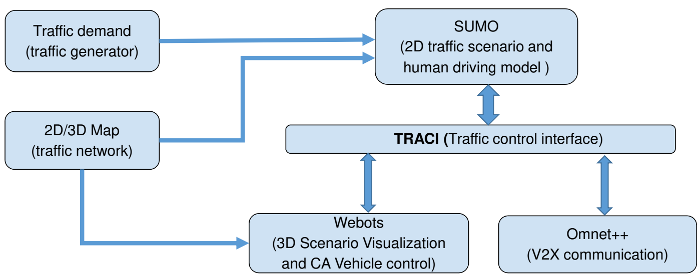

Figure 1. Framework of simulation platform

The proposed simulation platform can provide a realistic traffic environment (e.g. map topology, communica-tion and traffic infrastructure, traffic demands, etc.), support different types of vehicle dynamics and driving behaviours including human-driven and CA vehicles, and be capable of simulating scalability.

Keywords: *Connected and automated driving, simulation platform, cyber-physical system*

EXTENDED ABSTRACT ONLY

The effect of risk propensity on the crash risk: Evidence from lottery sales and fatal crashes in Texas

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Abstract: In economics, risk propensity refers to an entity's willingness to take on additional risk for additional gain. Risk-seeking (-averse) individuals are willing to take on additional risk even (only) when additional gain is low (high). Intuitively, compared to risk-averse drivers, risk-seeking drivers, in exchange for the additional gain in terms of shorter travel time or more convenient travel plans, are more likely to exhibit aggressive driving behaviors, such as speeding, driving with blood alcohol content (BAC), and driving under bad weather or road conditions, which in turn lead to the higher traffic crash risk.

Previous studies have investigated the effect of risk propensity on the crash risk using the survey data. Nevertheless, the studies using the survey data are usually subject to limitations such as small sample sizes, selection biases, and self-report biases. For example, survey subjects in the traffic safety studies may want to hide their propensities of risk-seeking or their histories of traffic rule violations or crashes. To address these limitations, we employ an empirical design, which covers all the population and fatal crashes in a state in the US, Texas, to investigate the effect of risk propensity on the crash risk. Specifically, we use lottery sales in a county to proxy for the risk propensity of all residents living in the county and use the number of fatal crashes to measure the crash risk. The lottery play is considered a risk-seeking behavior in that the cost of a lottery ticket is always lower than its expected return. We hypothesize that in a county, the lottery sales are positively related to the number of crashes.

Consistent with our hypothesis, we identify a positive relation between lottery sales and fatal crashes in a sample of 254 counties in Texas. Figure 1 depicts the relation between *Sales (00$)* and *Log(Crash 6Yr)*. *Sales (00$)* is the lottery sales per a hundred persons in a county in 2009, while *Crash 6Yr* is the annualized number of crashes during 2006-2011 per a million persons. In a simple regression, the coefficient of *Sales (00$)* at 0.260 suggests that an increase by one dollar in *Sales (00$)* is associated with the 26.0% increase in *Crash 6Yr*. Moreover, we show that the positive relation between lottery sales and fatal crashes are robust to a variety of alternative measures of crashes, such as the measures constructed in different time windows, normalized by vehicle miles traveled (VMTs), and focusing on local roads and local drivers. These robustness tests collectively further confirm the effect of drivers' risk propensity on the crash risk. This study contributes to the literature on individual choices, risky driving behaviors, and hotspots with high crash risk.

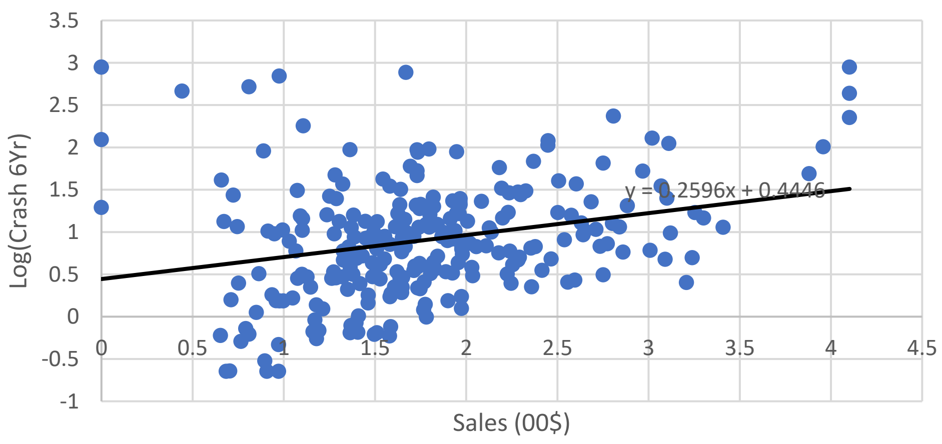

Figure 1. Relation between lottery sales and crashes

Keywords: *Risk propensity, crash risk, lottery sales, fatal crashes*

Routing strategy using local information based on a two layer cellular automaton model

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Abstract: A reliable and efficient traffic network model is required to study urban traffic congestion, which has increasingly become a global concern recently. The model can then be used to emulate different policy scenarios to assess different mitigation strategies, which will be very useful to policy- and decision makers. In this work, we develop a physical traffic model that can be used to investigate the intrinsic property of city traffic under different human decisions and driving behaviors. Cellular automaton is one of the most commonly used traffic network model. At its simplest stage, however, it can only model a one-dimensional problem. The Biham-Middleton-Levine (BML) extends the capability of the cellular automaton model to model a two-dimensional traffic network problem. However, it can only model two directions: rightward and downward. Directly modeling the four directions of traffic using the BML model causes jamming and gridlock problem. Thus, the existing traffic network models have not been sufficiently capable of modeling the traffic situation realistically. In this work, we propose a two-layer network modeling to address this intrinsic gridlock problem, where each layer is modeled based on the cellular automaton approach. The model is developed on a two-dimensional L^2-square lattice system, and users can specify the vehicle density prior to running the simulation. A moving strategy is then derived for each vehicle based on the origin and destination cell locations, where the shortest path is typically assumed. One of the key purposes of this work is to present the city traffic in a physical way to investigate the inertial characteristics of city traffic and to help bridge the gap between the simplified cellular automaton models and the complexity of real-world traffic. As such, we incorporate *driving behavior* modeling into the two-layer network system by introducing a flexibility index. Essentially, this index denotes the probability that a driver can deviate from the predefined shortest path when congestion occurs, i.e., when the next cell in its intended moving direction is occupied by another vehicle. The rationale behind this feature is that in real situation, drivers have the option to take an alternative path. We perform a number of traffic simulations to demonstrate the derived model and to gain insight into the effect of flexibility on the overall traffic flow. In particular, we vary the lattice size (by varying L) and the traffic density ρ, which will determine the number of vehicles to be simulated. Each vehicle is assigned a random origin-destination pair, and the corresponding moving strategy is then determined. By plotting the average vehicle speed as a function of vehicle density, we can find the phase transition point, where the traffic changes from a free-flow state to a congestion state. Our results show that when drivers are more flexible, the onset of congestion state is delayed to a higher density value. In other words, for the same density value, introducing a higher flexibility results in a higher average speed. This suggests that the vehicles can reach the destination faster, even if they need to cover a longer travel distance. This hypothesis is confirmed as we observe the effects of flexibility on the total distance traveled and the total number of completed journeys. Overall, our simulation results are consistent with the real traffic situations. This model can be further extended to mimic the traffic network more realistically by introducing more complexity in the system (e.g., the system lattice layout). As such, we will be able to evaluate some scenarios that the existing traffic models can not emulate accurately, such as the effect of traffic disruptions on the overall network flow.

Keywords: *Traffic model, network modeling, cellular automaton, driving behavior*

EXTENDED ABSTRACT ONLY

Urban Service Levels: Measure, monitor and mobilize

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Abstract: It is proposed that a set of consistent measurements and units of what makes cities work for their residents is possible. There are scales of population, density, economic impact, health, wellbeing, family and others that rely on certain investments be made in public transport, public open space, land use and social amenities. Together these will reflect an overall Level of Service (LOS) commensurate to the needs, and success, of a city. The calculations of the needs and the service-level comprise an effort towards observing and benchmarking of the urban landscape. This will bring the disparate and sometimes remote professions of traffic engineering, transport planning, land use planning, urban design and landscape architecture – at least - together into one platform.

Flexible and transparent assumptions can be made towards specific outcomes. The methods described will inform the best of policy lever application and decision making at high level political or grassroots community activity in deliberately choosing a future of their making. The graphic model will be easy to interpret, with transparent assumptions and flexibility while working to anchor a discussion. The measurements and outcomes anticipates furthering urban science.

As cities – or more precisely 'precincts', the smaller scale of urban redevelopment - grow in population, they require growth in infrastructure. We intuit that cities require increasing service levels to maintain or become great places of living, innovation, recreation, arts and technology. Although discussed in geography and urban planning, what hasn't been made express is a scientific measuring of just what levels of service makes for the best of living conditions and highest success. Indeed not only is it not done inside the planning departments, there are heard calls to not 'plan-by-number", referencing often gaudy 'paint-by-number' art kits. But numbers and data are what utilities, traffic engineers, accountants use and are understood by decision makers. Numbers are especially pressing for the hyper-connected modern cities growing at unprecedented rates around the world which will house people and jobs, innovations for - and dreams of - a better life. We need both qualitative and quantitative matters to weigh in our decision tree.

Germane to the debates regarding investments by tiers of governments is the question: which services support positive long term growth and which services have other effects? For example, at delivering productivity are investments in road or rail more likely to generate agglomeration benefits and crate value? Likewise, the importance of parks and trees, local schools and community centres need to be considered. Although there are many contemporary specialists on the topic ranging from New Urbanism suggesting nostalgia, Landscape Urbanism offering ecology, Smart Growth recommending less automobile-orientation as a basis for policy levers, Donald Shoup inspired *Shoupistas* asks us to calculate the values of free parking, but everywhere there is a great lack of specificity or a measure of cumulative impacts. Meanwhile, non-specialists, the other 99% of people, just want to get to work on time and have more time to enjoy living. The model can make rational and increasingly apparent the specifics and the impacts of choices made.

Therefore it is posited that: **There are scales of population size and density at which cities require investments in services to maintain or continue positive living conditions.** Without these services, it will be difficult for any city to maintain or achieve the next suite of targets such as jobs & housing balance, transport mode splits, public open space quality or GHG reduction not to mention poverty alleviation. This is not entirely new, but what is novel is the transparent relationship developed in the model. The model's outcomes and scenarios will be presented for comments and critique.

In short, we can calculate the core components of what most citizens anywhere might need to be self-actualized, and in turn help their cities become even more prosperous and equitable. It requires citizens to understand the pay-offs and trade-offs and for cities to invest properly with a series of scaled services.

Every time we enjoy the sun or the shade, with a friend or new acquaintance, with a view, in safety, with a fresh coffee, we need to consider all the values at play that have encouraged us to have such an opportunity. How do we get more of this?

Keywords: *Urban, trade-offs*

Meta-moderation for crowdsourced disaster management and urban participatory applications

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Abstract: This paper presents the Enterprise Meta-moderation of Innovation (EMI) system, which was designed, developed, and deployed to drive innovation in MTR Corporation, Hong Kong. Although EMI was designed specifically for use in an organisation, the system can potentially be extended to serve other useful functions in society. Hence, an important aspect of this paper involves identifying and discussing key considerations that need to be addressed in order for such a system to be used in crowdsourced disaster management and other urban participatory applications. The study highlights the role of agent-based modelling in better addressing some of the socio-technical challenges identified.

Keywords: *Meta-moderation, agent-based modelling, crowdsourcing, disaster, urban participatory approach*

Multi-objectives evaluation framework: A comparative study on the relationship between urban form and key environmental performance indicators in Tianjin Eco-city

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Abstract: This study is a continuity of the previous studies done at the Centre for Sustainable Asian Cities in discussing the relationship between density, urban form, urban environmental performance, urban sustainability, and the relationship between these domains. A quantitative framework to evaluate the key environmental factors affecting physiological & psychological comfort and building energy consumption was developed and demonstrated. The framework involves simulations on façade Vertical Daylight Factor, façade and envelope Sky Exposure Factor, urban surface Sky View Factor, and envelope annual cumulative irradiance at precinct scale in the context of the Tianjin Eco-city. The results highlight the presence of strong and significant correlations between urban form characteristics and key environmental performance indicators. These correlations are useful to inform the primary and secondary planning & design parameters that may affect each performance area and to understand the differences in the impact of each design parameters on various performance areas.

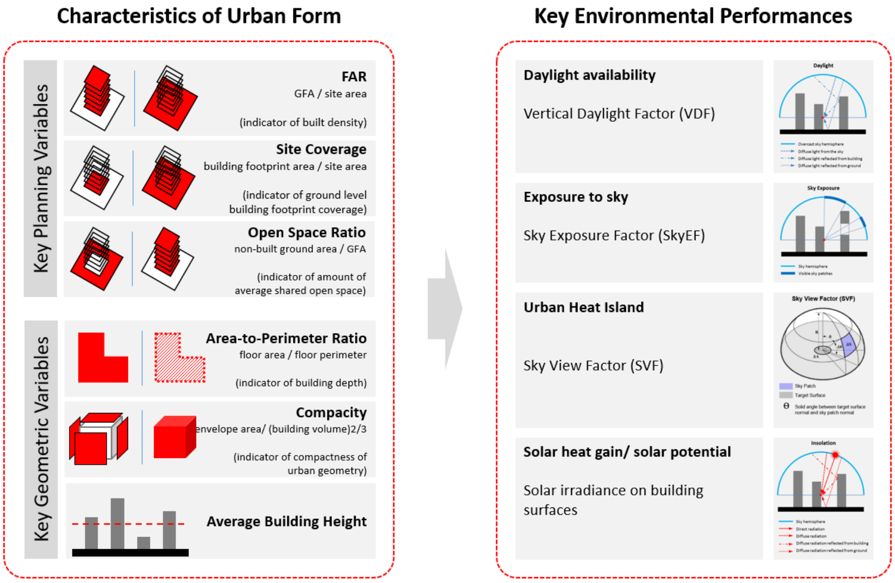

Figure 1. Relationship between design & planning variables and key environmental performance indicators explored in this study

Keywords: *Meso-scale study, multi-objectives evaluation workflow, key environmental performance indicators, sky exposure factor*

Hydrogen as a future fuel, challenges and opportunities: An overview of modelling approaches

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Abstract: When consumed, hydrogen produces water and energy but no greenhouse gas emissions. This great advantage has attracted many governments and industries around the world that aim to decrease their emissions and the number of policies and projects supporting clean hydrogen industry is increasing quickly. Yet, the implications of hydrogen industry at large scale is uncertain. In this paper, we provide an inventory of the techno-economic models that have been developed and /or can be adapted to investigate the opportunities and challenges of hydrogen as an alternative energy resource for Australia. We review 8 well-known techno-economic models and categorised them based on their characteristics including type, regional and time scale and the inclusion of gas and electricity systems. In the next step of this study, we will look into the key Characteristics related to future fuels such as inclusion (or the capacity of inclusion) of carbon accounting, and energy storage solution.

Keywords: *Techno-economic modelling, energy resource, hydrogen, energy network*

Bayesian uncertainty analyses of Great Barrier Reef catchment water quality model parameters without likelihood assumptions

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Abstract: Catchment water quality modelling is used as part of the Paddock to Reef program to assess the impact of land management changes across the Great Barrier Reef (GBR) catchments against water quality targets. It is necessary to have confidence in model performance in order to use them effectively for management and decision-making. Thus calibration, uncertainty and sensitivity analyses of model parameters are critical to optimise their predictive capability and thereby help facilitate better targeting of improved management practices.

Average annual loads estimated at end-of-systems (EOS) sites are likely to represent cumulative effects of various water quality processes. As a result, the calibration and uncertainty analyses of model parameters becomes a challenge.

Employed together, adaptive Sequential Monte Carlo sampled Approximate Bayesian Computation (SMC-ABC) and machine learning trained surrogate models offer an efficient framework for the calibration and uncertainty analyses of water quality model parameters. The appealing feature of Approximate Bayesian Computation when compared to formal Bayesian analysis is that it overcomes the requirement for an explicit likelihood function. As a compromise, an empirical approach is employed to stochastically sample from the unknown likelihood. This process can be computationally expensive when samples require the evaluation of a numerical models such as a catchment water quality model. To overcome this burden, machine learning techniques can be used to synthesise and train an efficient surrogate model to substitute for the functionality of the primitive model in the ABC algorithm.

This paper demonstrates the application of this combination of technologies for the calibration and uncertainty analyses of parameters that represent the transport of fine-sediment and particulate nutrients in two GBR basins namely the Pioneer River and Sandy Creek basins.

The comparison between fine-sediment streambank erosion estimated by the selected model along the O'Connell River between 2010 and 2014 against that estimated by the O'Connell River stability assessment (ORSA) was encouraging. Estimate by the selected calibrated model was only 1.6% greater than the ORSA estimate.

Average annual fine-sediment and particulate nutrient loads estimated by the calibrated model at the Pioneer River EOS site were within +/- 9% of that estimated by the GBR catchment loads monitoring program (GBRCLMP). Average annual fine-sediment and particulate nutrient loads estimated by the calibrated model at Sandy Creek EOS site are within +/- 3% of that estimated by GBRCLMP. Analysis of model parameter uncertainty reveals that all GBRCLMP estimated average annual constituent loads lie within the 95% credibility intervals of the modelled data.

This work demonstrates that employed together, SMC-ABC and machine learning trained surrogate models offer an efficient and powerful framework for the calibration and uncertainty analyses of GBR water catchment quality model parameters.

Keywords: *Water quality modelling, calibration, uncertainty, approximate Bayesian computation*

Purpose-focused and multiple-method sensitivity and uncertainty analysis of a catchment water quality model

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Abstract: Sensitivity analysis and uncertainty quantification are important steps in model evaluation and improvement. In Australia, the eWater Source Catchment Modelling Framework has been used as the tool to develop the Great Barrier Reef (GBR) Dynamic SedNet models and report on progress towards the Reef Plan water quality targets. The current complexity of the Source modelling framework has significantly impacted on run time efficiency. Slow run times have meant that GBR modellers have not been able to rigorously assess parameter sensitivity and uncertainty aspects of the Dynamic SedNet Source models. To address this gap, a project commenced in 2017 to develop methods for systematic sensitivity and uncertainty analysis of the GBR Dynamic SedNet catchment models to assist model development and improvement through the identification of the sensitive parameters to prioritise future data collection and secondly to enable reporting of loads uncertainty to stakeholders.

In this presentation, we report the methods and results of the sensitivity and uncertainty analysis of the Dynamic SedNet Source catchment model, using the Mackay Whitsunday region as a case study. The analysis has two characteristics: purpose-focused and employing multi-method. The investigation focuses on three modelling purposes:

- The Report Card to show changes in constituent loads following changes in land management practices
- Fine sediment load prediction
- Source differentiation in fine sediment contributions

Depending on the purposes, various analytical and simulation methods are used collectively to investigate the uncertainty of the model water quality model outputs (with varying quantities of interest) and the sensitivity of model outputs to model inputs and parameters. Analysis of model component equations and Monte Carlo simulations are used to quantify model output uncertainty, whereas algebraic and One-at-a-time (OAT) sensitivity analyses are used to investigate model inputs and parameters sensitivity.

Key conclusions from the investigation include:

- Uncertainty assessments are context-dependent, and the sources and levels of uncertainty differ depending on the purpose of modelling. In the catchment water quality modelling context, load prediction often dominates the uncertainty analysis in the literature, whereas the model outputs are often used to report change in loads or constituent source differentiation. Thus, we need to be explicit about the context of uncertainty assessments and divert more efforts into purposes other than load prediction.
- Multi-method sensitivity and uncertainty analysis has several benefits. Firstly it allows comparison of analysis findings, thus providing more confidence in analysis outcomes. Secondly, the findings from one method can support/inform the analysis choice of another method. Thirdly, the findings from different methods, tailored to address different aspect of the model sensitivity and uncertainty, enrich our understanding in model behaviours.

Keywords: *Water quality, uncertainty, Source*

Tipping points and early warning signals in coral reef ecosystem models

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Abstract: Detecting signs that an ecosystem is about to undergo a rapid regime shift is an ecological question of increasing relevance to our changing world. Systems typically exhibit characteristic behaviours, such as increasing temporal autocorrelation or increasing variance, when they are about to undergo major change in qualitative behaviour. Such early warning signs can then be used to predict that a system is approaching a tipping point and may experience a rapid collapse. However, such signs are not universal and some systems may instead undergo slow change even when they approach or pass a tipping point. This means that major changes in qualitative dynamics may not be readily apparent in observations, presenting a challenge to detect such thresholds from ecological data.

Coral reefs have been shown to exhibit alternative stable states in relation to loss of resilience and exposure to stressors. Coral reefs are also one of the most stressed ecosystems on the planet, with the both natural disturbances and human-induced pressures that are only set to increase with climate change and deterioration of environmental conditions in oceans worldwide. Models of coral reefs thus allow us to examine relationships between tipping points, as well as our ability to detect early warning signs of possible collapse, in complex yet sensitive ecosystems exposed to multiple stressors and disturbance regimes. We used models of coral population dynamics on Australia's iconic Great Barrier Reef to investigate the nature of dynamics and warning signals that such complex ecosystems could collapse in future. We employed both conceptual and process-based models to simulate conditions that could lead to tipping points and eventual collapse of coral populations on reefs, and therefore potential whole-of-ecosystem collapse due to the loss of critical habitat building species. This provided us with insights not only about the limitations of the observations when devising such predictions, but also to suggest how observations can be modified to more readily capture potential early warning signs of critical transitions. Understanding tipping points and developing new methods to detect them in observations and data is becoming increasingly important as the impacts of climate and anthropogenic stressors on ecosystems become increasingly more intense and unpredictable.

Keywords: *Tipping points, critical transitions, early warnings, coral reef, ecosystem model, climate change*

Streamflow simulations for gauged and ungauged catchments of the Great Barrier Reef region using a distributed hydrological model

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Abstract: The eReefs project aims to protect and preserve the iconic Great Barrier Reef (GBR) in support of the Reef 2050 Plan. The Water Forecasting Services team at the Bureau of Meteorology in collaboration with eReefs project partners has developed water quality and quantity (streamflow) models for the GBR catchments. These models for the catchments draining to the GBR coastline, in turn, provide the inputs to marine hydrodynamic and biogeochemical (BGC) models used to assess changes in the marine environment and to provide information for the Annual Reef Report Card. The Report Card aims to summarise the condition of the marine environment for the purpose of detecting changes in response to various land-use/land-cover management actions. To meet the requirement for streamflow information in the marine/BGC modelling for the Reef Report Cards, the Bureau has developed a distributed hydrological model to generate historical simulations, nowcasts and forecasts for the gauged and ungauged areas of the GBR catchments.

The physical-conceptual distributed hydrological model Grid-to-Grid (G2G) from the Centre for Ecology & Hydrology (CEH), UK is used for modelling the GBR catchments. G2G is deployed operationally as a countrywide flood forecasting system by both the Flood Forecasting Centre across England and Wales and by the Scottish Flood Forecasting Service over Scotland. G2G has been configured over the entire 426,000 km^2 area draining to the GBR coastline, of which 76,600 km^2 (~18%) is ungauged (that is, the area between the most downstream gauging locations and the coastline). The ungauged area is located along the coast and experiences higher rainfall than inland, and it contributes significantly to the water volume discharging along the coast. G2G has been applied at a 0.01° (~1km) spatial resolution and at an hourly time-scale. G2G is underpinned by: (i) spatial datasets on terrain, land-cover, soil and geology, and (ii) hydro-meteorological time-series of streamflow and gridded rainfall and potential evapotranspiration. The global, local, artificial influence, and error-predictor parameters of G2G are calibrated over the model domain using the gauged streamflow. G2G state-updating and flow-insertion options for data-assimilation of streamflow are used when generating historical simulations and forecasts. The Nash-Sutcliffe Efficiency (NSE) measure of model performance is calculated at gauged locations for historical simulations (2007 to 2016), and found to give reasonably high values for a majority of locations (Figure 1). As an emulation of operational conditions, 3-day streamflow forecasts have been produced using rainfall forecasts from the Australian Community Climate and Earth System Simulator – Regional (ACCESS-R) numerical weather prediction model for the period 2013 to 2016.

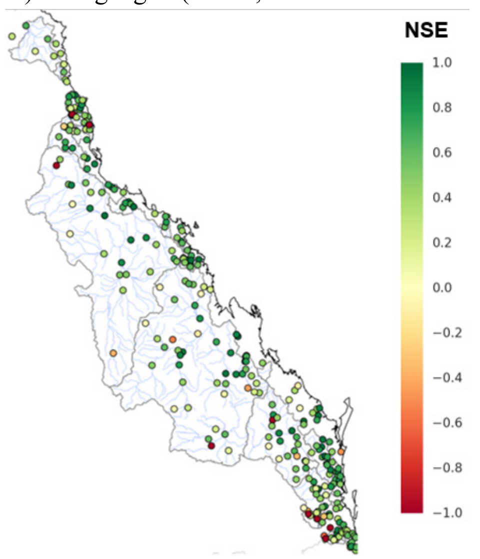

Figure 1. Performance (NSE) of hourly historical simulations over 2007 to 2016

Simulated G2G streamflows draining to the GBR are aggregated along stretches of the coastline to provide the total streamflow volumes at 60 CSIRO marine modelling nodes. The contribution of water volume from the ungauged area is ~31% of the total whereas the ungauged area is only ~18% of the total catchment area.

Keywords: *Streamflow, historical simulation, ungauged, distributed hydrological model, Great Barrier Reef*

Towards Ecologically Relevant Targets: Impact of flow and sediment discharge on seagrass communities in the Great Barrier Reef

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Abstract: Catchment degradation causing increased sediment flow is one of the key stressors facing Great Barrier Reef (GBR) habitats. Ecologically relevant targets (ERTs) for sediment and nutrient loads have been previously proposed based on seagrass light requirements, the next step is to connect these to ecological response. The overarching goal of the present work is to recommend preliminary thresholds that can be used in the development of more refined ERTs. To achieve this, we perform statistical analysis on datasets for catchment flows and sediment loads and condition of the adjacent seagrass habitat, to identify what might be the direct impacts of catchment discharge on seagrass and the associated timescales of ecological response.

Our case study focuses on Cleveland Bay, which is located in the central GBR, and has important seagrass habitat that is affected by discharge from the Burdekin River. Annual monitoring of seagrass biomass and area has been undertaken since 2007. We compare these ecological time-series with data for Burdekin River annual flow and total sediment load from 2005 onwards.

Annual Burdekin River flow varied by nearly 40-fold within the 2005-2018 study period, and declines in biomass and area of both subtidal and intertidal seagrasses were associated with high flows and loads from the Burdekin. Subtidal seagrasses appeared more sensitive to changes in catchment discharges than intertidal seagrasses, exhibiting a 3 year timeframe for recovery, following high annual flows and loads.

Based on our results, a linear model relating change in seagrass biomass to Burdekin River metrics was used to calculate *predicted thresholds* below which seagrass biomass was likely to increase, and above which biomass was likely to decline. For seagrass area, a *growth threshold*, below which seagrass area expanded; and a *decline threshold,* above which seagrass area fell, were defined for annual Burdekin River flow, and sediment load. Overall these thresholds provide the first steps towards refining ERTs based on ecological condition, which can directly inform the management of the GBR to protect its iconic seagrass habitats and associated communities. The next step is to examine whether the relationship between river discharge and sediment load was the primary cause of seagrass decline.

Keywords: *Seagrass, sediment, ecologically relevant target, catchment loads*

Xenobiotic compounds in the Great Barrier Reef catchments: modelling temporal dynamics

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Abstract: Xenobiotic compounds such as pesticides, herbicides, fungicides and insecticides have been detected in the waters and sediments in the Great Barrier Reef marine ecosystem. These are of concern due to the deleterious impact of these compounds on corals and organisms within the Great Barrier Reef (Brodie et al. 2012). There is a need to be able to identify when and where xenobiotic levels are highest in the Great Barrier Reef catchments in order to target and prioritise management actions to reduce the level of these xenobiotic compounds reaching the Great Barrier Reef. This requires: (i) a better understanding of the key factors affecting the level of xenobiotics present in the riverine water entering the Great Barrier Reef, and (ii) models that will be able to predict key hot spots and hot moments of xenobiotics in the Great Barrier Reef catchment. In this preliminary study, we focus on the impact of streamflow on xenobiotic concentrations (focusing on Atrazine, Diuron and Imidacloprid) in the Great Barrier Reef catchment and develop simple statistical models to predict the concentration of these compounds in the rivers in the Great Barrier Reef catchment.

Event-based monitoring data of Atrazine, Diuron and Imidacloprid collected as part of the Paddock to Reef Program (Queensland Government, 2018) between 2009 and 2016 at five sites (Table 1) were used for this study. Streamflow and total suspended solids (TSS) concentration data for these sites were also obtained from the Paddock to Reef Program. All water quality and streamflow data were log-normalised prior to further analysis. We use a Tobit modelling framework (Remy and Wild, 2017) to solve statistical linear regression models that link in-stream xenobiotic concentrations with streamflow and TSS at each monitoring location. The Tobit framework allows us to incorporate censored data (i.e., concentrations below the detection limit) in our models. The models were solved using a Bayesian approach.

Table 1. Regression coefficients of statistical models for each site

Site Number	Site Location	Regression coefficient of streamflow (95% Confidence Interval)			Regression coefficient of TSS (95% Confidence Interval)		
		Atrazine	Diuron	Imidacloprid	Atrazine	Diuron	Imidacloprid
1240062	O'Connell River at Caravan Park	0.23 – 1.09	0.19 - 1.2	0.35-0.89	0.80-1.5	0.59-1.5	0.59-1.00
119101A	Barratta Creek at Northcote	~0	0.13 - 0.63	0.074 - 0.83	0.017-0.36	NA	0.34-0.93
125013A	Pioneer River at Dumbleton Pump Station	0.21 – 0.56	0.17 - 0.64	0.44- 1.06	~0	~0	0.19-0.54
126001A	Sandy Creek at Homebush	0.28-0.65	0.48-0.92	0.42 - 0.74	0.32-0.60	0.40 - 0.73	0.41-0.63
136014A	Burnett River at Ben Anderson Barrage	~0	~0	~0	0.25-0.64	~0	~0

The importance of streamflow and TSS as predictors for xenobiotic concentration in the river was assessed using the magnitude of the regression coefficient for streamflow and TSS (Table 1). The preliminary results of this study indicate that: (i) for some sites, streamflow and TSS are important predictors of in-stream Atrazine, Diuron and Imidacloprid concentration; (ii) there is significant variability in the relationship between xenobiotic concentrations and streamflow and TSS between sites, which needs to be further investigated.

Keywords: *Pesticides, herbicides, statistical modelling, censored data*

A Keras Neural Network to emulate eReefs turbidity

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Abstract: eReefs model simulates hydrodynamics, sediment transport and biogeochemical processes in the Great Barrier Reef (GBR) region in near-real-time. Daily snapshots of the simulated data are accumulated into data repositories which can be accessed remotely via the web (https://research.csiro.au/ereefs/). These data provide an opportunity for the research community to experiment with digital images of the GBR region. This paper summarises preliminary results from the application of the Keras framework to such data. Keras is an open-source neural-network library written in Python and capable of running on top of TensorFlow. Designed to enable fast experimentation with deep neural networks, it makes the development of new networks user-friendly, modular, and extensible. As a test case-study we used Keras to build and evaluate a relatively simple neural network (emulator) predicting simulated turbidity in the GBR region. The study was motivated by a number of reasons including the need for a quick evaluation of management scenarios in the GBR region.

To accelerate the development of the emulator, a subregion of the GBR shelf centred around Burdekin river and truncated to 100m depth has been selected. Only surface cells were considered. For every individual grid cell and for a particular day, the network input variables (called features) comprised the water depth, the distance from the given cell to the river mouth, the direction towards the river mouth, the river load, wave period and amplitude, wind speed components (proxy to surface currents) and the content of mud in benthic sediments. The output variable was the water turbidity at a given cell. The input data was normalised and then shuffled and split into two parts one representing a training set to build an emulator and another set to test the quality of this emulator. The network comprised 4 layers with 11 nodes in the first input layer, 190 nodes in the second layer, 11 nodes in the 3rd layer and a single output node. The batch size was set to 128, and the number of epochs was 555. The network configuration was based on a number of numerical experiments with a randomly selected set of parameters.

The neural network was trained on a subset of data from 2011 and then tested against independent sets of data from the same year (2011). The results indicate a good agreement between emulated data and truth in 2011 (fig. 1), however, this emulator failed to generalise to 2012. During the presentation key challenges hindering the generalisation of such an emulator will be outlined and opportunities for the further development will be discussed.

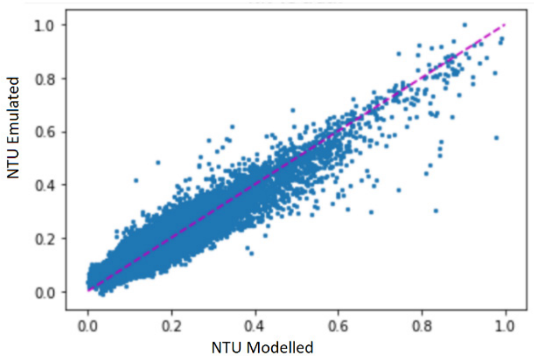

Figure 1. GBR turbidity emulated by Neural Network vs data simulated by model

Keywords: *eReefs, turbidity, neural network*

Understanding the impacts of pesticides on Great Barrier Reef Catchments: A systems thinking approach

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Abstract: Pesticide residues running from agricultural lands along Great Barrier Reef Catchments (GBRCs) has been recognised a serious threat to aquatic ecosystem health and become a priority management in the GBRCs. Pesticide concentrations have been detected in marine waters, sediments and seagrass meadows in the GBRCs. The Reef 2050 Water Quality Improvement Plan has been introduced to reduce the pesticide concentrations in aquatic ecosystems along the GBRCs. However, it is uncertain if the adoption of best pesticide management practices in agricultural production will meet these reduction targets and improve the GBRCs' aquatic ecosystem health resilience. A dynamic hypothesis was initially developed to illustrate possible patterns of ecosystem health risks by 2050 under multiple drivers and changing conditions (Figure 1). The relationships and interactions between pesticide applications and aquatic ecosystem health risks are a dynamic and complex system, and thus it requires approaches that can cope with dynamic complexity and enable decision-makers to systematically understand the system under multiple drivers for decision-making supports. This is a domain of systems thinking approach which has been proved to be a powerful tool to understand the complexity and dynamics in any system, such as the pesticide and ecosystem health risk system. The systems thinking approach assists decision-makers to examine different components within a system as a whole and as their interconnected nature, thereby increasing the development of effective policies in ecosystem health risk assessment and management.

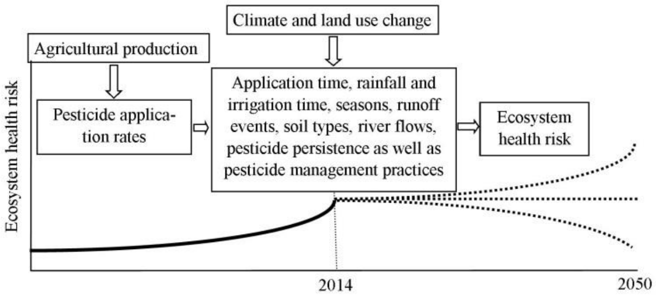

Figure 1. A dynamic hypothesis of ecosystem health risks of GBRCs under multiple drivers and changing conditions

Causal loop diagrams (CLDs) and system archetypes (SAs) are powerful tools and techniques of systems thinking approach. The CLDs describe the influences of variables (e.g. pesticide application time, rainfall and irrigation time, runoff events, soil types) on aquatic ecosystems in same (S) or opposite (O) directions. The feedback loops may occur either in a reinforcing (R) or balancing (B) loops, where R loops represent growing or declining actions in the system, and balancing loops are self-correcting mechanisms that counteract, and oppose change. A preliminary CLD of the pesticide and ecosystem health risk system (Figure 2) was firstly developed to visualise the relationships and interactions between pesticide applications and ecosystem health risk of the GBRCs. A final CLD will be then developed based on literature review results from published articles and technical reports investigating the impacts of pesticides on GBRCs. The final CLD will present a comprehensive representation of the drivers within the system as a whole and identify feedback mechanisms that link four different components in the system: (1) driving sources of pesticides and pesticide management, (2) pesticide transport, fate and detection, (3) ecological risks of pesticides and, (4) economics of improved land management practices in the GBRCs. The CLD will be then used to identify system archetypes (SAs) that are generic systems structures describing the common dynamic processes of the system. Analysing the SAs can assist decision-makers, growers and industrial stakeholders with the identification of system leverage points where an intervention should have the most influence on the improved aquatic ecosystem health resilience from pesticide applications.

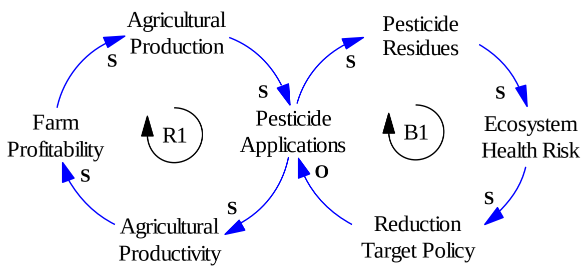

Figure 2*: A preliminary CLD of pesticide applications and ecosystem health risks in GBRCs. S: same direction; O: opposite direction; R: reinforcing loop; B: balancing loop*

Keywords: *Decision-making supports, ecosystem health risks, pesticide applications and management, Great Barrier Reef Catchments, systems thinking approach*

Predicting subsurface water temperature from sea surface temperature in the Great Barrier Reef

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Abstract: Coral reefs are at risk due to climate change, specifically extreme ocean warming events. Understanding how water temperature varies vertically in the Great Barrier Reef (GBR) lagoon is important for understanding the potential threat to coral reef ecosystems. Predictive modelling can be used to assess extreme temperature high risk areas. This study had two aims: (1) to compare vertical temperature profiles predicted by the eReefs 1 km resolution (GBR1) hydrodynamic model with observed temperature collected by Slocum gliders on the Great Barrier Reef (GBR); (2) to create a simple statistical regression model to quickly predict subsurface temperature on the GBR during the wet season down to 40 m given sea surface temperature (SST). First, profiles of eReefs and glider temperature from different regions, seasons and time of day were compared using bias, Root Mean Square Error (RMSE) and Willmott's Skill Score. Results show that temperature profiles predicted by the eReefs GBR1 hydrodynamic model are sufficiently accurate for the purpose of estimating impacts on corals. We then developed a new statistical model, Generalised Additive Modelling (GAM) was selected due to the nonlinear relationships between the subsurface temperatures and the explanatory variables. The GAM model built used five variables: SST, depth, time (days since October 1st) and location (as latitude and longitude) to predict temperature. The model produced RMSE values below 0.5°C and Pearson's correlation coefficients between predicted and observed temperatures above 0.90. This study provides a simple and accurate statistical model allowing prediction of subsurface sea temperature from observed or modelled surface temperature.

Keywords: *Statistical modelling, eReefs, Generalised Additive Model*

The erosion of an ideal gully under steady state conditions

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Abstract: Gullies are responsible for as much as 40% of the accelerated sediment reaching the GBR, contributing to poor water quality and impacting the health and resilience of the Reef. Improving water quality on the GBR is essential to provide the best opportunity to recover from past events and meet the challenges of climate change. The Australian and Queensland Governments aim to reduce sediment delivery to the Reef by 25% as part of the Reef 2050 Water Quality Improvement Plan 2050. Given the disproportionate contribution of gullies to the total sediment budget, reducing gully erosion will be an important part of meeting this target. The Prosser Report (2018) has identified process-based models of gully erosion as important to support the strategic remediation of gullies. Previous models have employed empirical or conceptual approaches, which are not well suited to be adapted to representing interventions to provide localised decision support. This paper presents a first step in the development of a locally focussed, process-based model of gully erosion that is capable of representing gully interventions.

The focus on water quality impacts on the GBR motivates the modelling focus on the concentration of sediment within the water column rather than on the evolution of the gully system. Gully erosion is therefore modelled using conservation of mass arguments, with entrainment of sediment from the gully walls and bed acting as a sediment source and deposition of sediment as a sink. The rate of entrainment is determined by balancing the power available to do work on the gully bed with the power required to entrain. The power available to do work on the gully is due to the stream- and waterfall-power of the system resulting from the loss of potential energy of the flow as it loses height. Adapting the approach of Hairsine and Rose (1992a,b) we introduce the concept of a soil cohesiveness factor, which represents the power required to overcome the cohesion of the sediment to enable it to be entrained. Together with a static friction term, this represents the streamflow threshold, the minimum amount of power required for entrainment to occur.

A key feature of this model is the inclusion of a depositional layer and the concept of re-entrainment after the model of Hairsine and Rose (1992a,b). Steady-state solutions for the area encompassed by the depositional layer are explored, which demonstrates that the power available to erode cannot be independent of the concentration and flow conditions. A sediment carrying capacity is therefore introduced, providing a simple mechanism to represent the energy requirements of transporting sediment in suspension. The adapted model is explored under the assumptions of a highly erosive bed, and shown to provide the expected behaviour. Exploration of the model demonstrates that the assumptions of a depositional layer, particularly at steady state, requires further consideration. The aerial approach to modelling the depositional layer, although consistent with observations at the laboratory scale, appears not to extend to natural high-flow events. This analysis suggests that an alternative modelling framework to capture the mechanism of re-entrainment is necessary.

The developed model is suitable to explore gully erosion impacts on water quality and the potential benefits of different interventions. We illustrate how different interventions can be represented in the model, however parameterisation to different interventions is yet to be undertaken. Future work will focus on improving the representation of the depositional layer, validating the model against observations, and parameterising the model including the representation of interventions.

Keywords: *Gullies, erosion, process-model, Great Barrier Reef,*

Benthic light as an ecologically-validated water quality indicator

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Abstract: Light is a key requirement of many marine species and is one of the main factors controlling the occurrence and health of corals and seagrasses in marine ecosystems. The amount of light in the relevant part of the spectrum that reaches the bottom of the water column is known as benthic photosynthetically active radiation (bPAR). Variations in water quality and depth combine to produce spatial and temporal variations in bPAR, which in turn affect benthic habitat quality. In the Great Barrier Reef (GBR), bPAR is influenced by river runoff, which carries sediments and nutrients from the land, as well as wind and tides. To manage the GBR, it is important to be able to monitor and quantify these impacts. We have developed a new water quality indicator based on monitoring variations in the area of benthic habitat exposed to a suitable bPAR regime over the course of each year.

To develop this indicator, we (a) measured the responses of *Acropora* and *Pachyseris* (coral) species to high, low and variable light conditions to determine ecological thresholds with respect to bPAR; (b) reviewed the literature regarding seagrass responses to light to determine seagrass-relevant thresholds; (c) developed a new Inherent Optical Property (IOP) based remote sensing algorithm for the GBR and used the algorithm to map daily integrated bPAR over sixteen years; and (d) developed a new, bPAR-based water quality indicator that can be used as a component of an over-all water quality index to help monitor the health of the GBR (**Figure 1).**

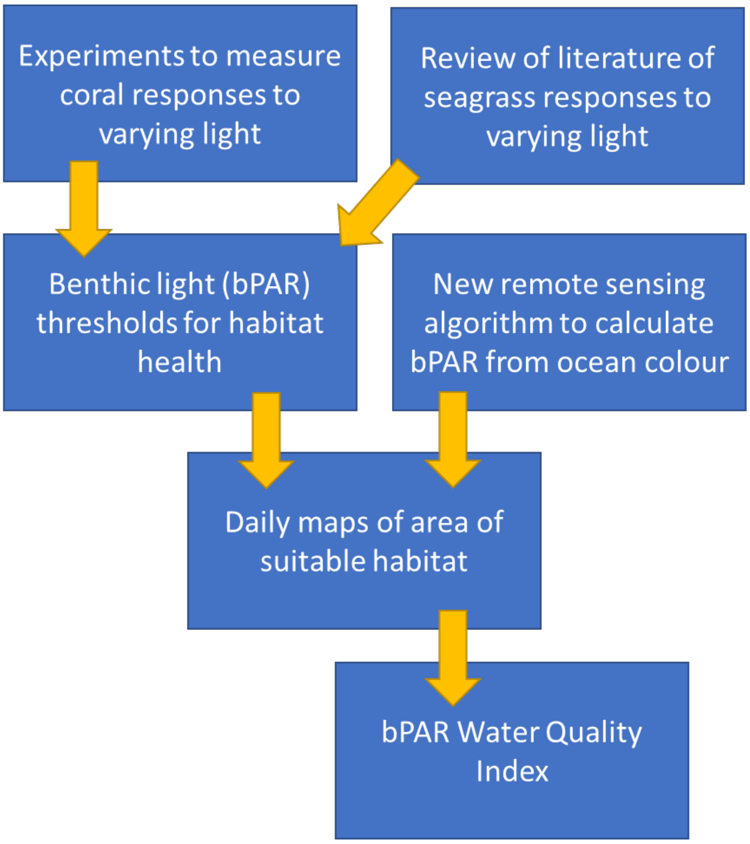

Figure 1. Steps involved in development of the new water quality indicator and index

The new bPAR water quality index has been calculated and converted to letter grades for each management region of the GBR. The index is sensitive to year-to-year variations in water quality associated with major storm and flood events and produces intuitive gradients from high scores in the northern and offshore parts of the GBR to lower and more variable scores in the inshore regions, especially in the south.

We are now working on operationalising this data product and evaluating the potential of the eReefs marine models for monitoring and predicting changes in this new, ecologically-validated water quality indicator.

Keywords: *PAR, WQI, benthic habitats, GBR, light*

POMDPs for Sustainable Fishery Management

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Abstract: The challenge of sustainable fishery management is to design harvest policies that attain the dual objectives of: (a) protecting the species from over fishing, and (b) ensuring adequate economic return to fishers. It is clear that a suitable compromise between these two, conflicting, objectives must be achieved. However, a major difficulty stems from the need to deal with various sources of uncertainty associated with the fluctuations of the population, such as sea-surface temperature, pollution, or levels of nutrients. This is further complicated by the uncertainties associated with the effects of the management decisions and fishing pressure.

Partially Observable Markov Decision Processes (POMDPs) provide a natural mathematical framework for incorporating these uncertainties in the decision making process. This was already recognised by several authors. However, the promise of POMDPs has not yet been realised because they are provably computationally hard to solve in general, and for many years were considered to be solvable only for toy problems. In addition, the underlying dynamics of fish populations are normally described by deterministic difference or differential equations and it is not entirely clear how these should be incorporated into the stochastic dynamics of POMDPs.

This paper summarizes a, still preliminary, study that tackles both of the above problems. In particular, the computational complexity problem is tackled with the help of suitable discretization of state and action spaces and DESPOT; a state-of-the-art POMDP solver. In addition, the deterministic dynamics of the widely used Beverton-Holt model are modified to incorporate stochasticity in both the proliferation rate and in the observations based on catch and the outputs of the latter model.

The resulting POMDP formulation takes into account some of the uncertainties in managing fisheries, and shows that an adaptive management policy can be more advantageous than a simple fixed action policy. We also report on experiments with various modelling choices and their effects on the resulting policy.

Finally, recognising that POMDP policies are sometimes hard to interpret, we demonstrate that our adaptive management policy possesses an attractive feedback (or closed-loop) structure. Namely, the actions selected by that policy depend on the current expected biomass of the harvested species. Effectively, the policy maps the current expected biomass to a decision to use certain harvest levels in prescribed proportions. Naturally, when the expected biomass is low the more conservative (i.e., lower) harvest actions are preferred. On the other hand, when the expected biomass is high, actions corresponding to higher harvest levels are selected. Nonetheless, the most intensive (i.e., greedy) harvest levels are never selected because of the sustainability concerns.

Keywords: *POMDPs, sustainability, fishery management*

Robust decision support for achieving sustainability in cities and communities: Connecting sustainability knowledge and local actions

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Abstract: The unanimous adoption of global sustainability frameworks such as the United Nation 17 Sustainable Development Goals (SDGs) signals a strong ambition for addressing concerns around the impacts of human activities on natural and ecological systems. In recent decades, there has been a proliferation of resources to enable the implementation of these global frameworks across spatial scales, businesses, and sectoral domains. Examples are sustainability indicator dashboards with an abundance of data about past, present, and future (estimate) of climatic, environmental, and ecological conditions. The resources also include analytics and inferences about (e.g., climate adaptation or land-use) pathways to sustainability that are developed through integrated modelling and high-performance computing, supported by available databases.

One crucial challenge here is overestimation of the ease of use of available databases, decision analytics, and suggested inferences. A typical user of these resources can be a council officer of a local community who has newly become responsible for the implementation of a sustainability framework and who has a different primary job. Local actors often have a limited knowledge of the complexity of coupled human—natural systems to analyse and understand potential impacts and solutions from available raw datasets. They may also have limited time, financial resources, and skills to implement decision analytics and pathway frameworks. This knowledge gap between what the sustainability knowledge provides and what local actors need is compounded by global uncertain change emerging from the limited and contested knowledge of the future, missing data, inadequate theories, and conflicting views about boundaries and the relative importance of the outcomes, termed as *deep uncertainty*. Another challenge is that inferences and pathways for achieving sustainability are often designed at an aggregated (global and national) level whereas legitimate and credible pathways to sustainability require acknowledging the heterogeneity of (e.g., geographical, demographical, and economic) contexts and alignment with their local characteristics and priorities.

We develop a robust decision support platform that enables successful implementations of the broad and abstract global/national sustainability frameworks into pragmatic plans that are tailored to specific socio-economic and environmental characteristics of local contexts. The platform also promotes a move away from traditional predict-then-act planning approaches towards iterative anticipatory approaches that result in *robust* decisions insensitive to deep uncertainties based on an in-depth evaluation of highly precautionary or risk-averse decision alternatives. The platform is going to be an enabling environment:

- Providing a *structured, interactive process* that guides local actors in cities and communities through the sequence of iterative steps to develop, evaluate, implement, and monitor locally-relevant pathways to sustainability;
- Equipping local decision-makers with accessible and jargon-minimum *tools and methods*, for example for data visualisation and decision stress-testing, to support each step with a careful consideration of the cognitive barriers of potential users;
- Embedding (or at least facilitating access to) available *databases* with option to update/replace existing or missing data with locally available information for the implementation of tools and methods;
- Enabling an in-depth *engagement* with local stakeholders to achieve an inclusive and democratic implementation of sustainability aspirations by incorporating a diverse range of social groups, including marginalised and vulnerable people, through networking opportunities, for example, online forums, social media, workshops, and training.

***Keywords**:* *Decision, model, participatory, uncertainty, sustainability*

A participatory framework for evaluating Sustainable Development Goals under future uncertain change

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Abstract: In 2015, the UN member states unanimously adopted the Sustainable Development Goals (SDGs) as a global framework for achieving socio-economic ambitions as well as environmental agendas. This framework has been implemented primarily from a top-down perspective thus far, with states outlining and pursuing the fulfilment of 'national' agendas. However, a top-down approach can prematurely aggregate the diversity of perspectives and ignore the heterogeneous distribution of resources and skills at local scales, resulting in national pathways that are *socially* vulnerable to local conditions.

This article proposes a participatory framework for the bottom-up implementation and evaluation of the SDGs at local scales (e.g. cities, communities, businesses) in the face of future scenarios, characterised by the Shared Socioeconomic Pathways (SSPs). SSPs were originally developed for climate change research and describe five global scenarios based upon challenges to climate adaptation and mitigation. They characterise scenario driving forces (or elements) and scenario narratives based on assumptions of outcomes from different levels of challenge to climate adaptation and mitigation. We adapted and customised the original SSPs to generate future scenarios for the broader sphere of sustainability (modifying the context) and at the local scale (modifying the spatial scale).

We used contextual analysis of the literature and expert consultation through a workshop setting to identify (i.e., translate and downscale) the SDG goals and indicators which were of greatest concern to our case study community. This created a *localised* shortlist of SDGs. Using this localised shortlist, we adapted ("extended") the scenario driving forces from the original SSP list to suit the SDGs (rather than climate change), in the context of the local community (instead of the global view). This allowed us to map the most influential scenario driving forces to the localised SDGs. We then developed different assumptions for each driving force under future uncertain change based on the contextual analysis of the literature and expert consultation. The aggregation of different sets of assumptions (i.e., distinct states) across 19 identified scenario driving forces (elements) resulted in five localised SSP scenarios. We evaluated the fulfilment of the localised SDGs under the five localised SSP scenarios based on expert judgement and available data in the literature.

Our participatory framework can deliver multiple benefits to the model-based analysis of pathways to sustainability: 1) The resulting state of driving forces and SSP narratives can be quantified and used as exploratory scenarios for the evaluation of the SDGs in the local community; 2) The framework can be a systematic tool to communicate driving forces and uncertainties around the SDGs to decision makers by providing a narrative description of the potential outcomes of a set of decisions; 3) Our framework can create an engagement platform for local communities to be involved in shaping sustainability pathways by downscaling global goals and creating scenarios relevant to the local area based on their needs and priorities.

Keywords: *Scenarios, Sustainable Development Goals, participatory, localisation, uncertainty*

Modelling animal disease control and post-outbreak management to improve outbreak response policies

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Abstract: The Foot and Mouth Disease (FMD) Ready project is a transdisciplinary collaboration that aims to strengthen preparedness and facilitate a return to trade for Australia in the event of an emergency animal disease (EAD) incursion, using FMD as a model. One component of this project is focused on developing decision support tools to inform decision-making in response to an outbreak of FMD.

Epidemiological modelling is increasingly recognised as a valuable tool for understanding the risks of FMD spread and control in the event of an outbreak. This presentation will discuss ongoing work to enhance the capabilities of Australia's national-scale model of livestock disease spread—the Australian Animal Disease Spread (AADIS) model—including approaches to post-outbreak surveillance and management options for vaccinated animals for proof-of-freedom and a faster return to trade. Nine outbreak scenarios with 13 different control strategies (11 of which include vaccination) were used to simulate FMD spread. Data from these simulations were used to support post-outbreak surveillance and economic analyses to evaluate the costs and benefits of different control strategies.

Preliminary results indicate control strategies that include vaccination may reduce the duration and size of an FMD outbreak when compared with a 'culling only' strategy in outbreak scenarios where disease is likely to spread most rapidly and exceed response resource capacity. However, in line with current international animal health standards, the use of vaccination and management of vaccinated animals during the post-outbreak phase may prolong the time taken to regain export markets. Decisions on whether vaccinated animals are removed from the population post-outbreak as part of the control strategy or retained in the population to live out their commercial lives could significantly impact the overall economic cost of an FMD outbreak in Australia.

This work brings scientists from across disciplines together with government and industry stakeholders to provide an innovative and integrated epidemiological-economic decision support system. Findings will strengthen strategic decision-making around disease management and reinforce Australia's evidence-based EAD preparedness policy.

This project is supported by Meat and Livestock Australia, through funding from the Australian Government Department of Agriculture as part of its Rural R&D for Profit programme, and by producer levies from Australian FMD-susceptible livestock (cattle, sheep, goats and pigs) industries and Charles Sturt University, leveraging significant in-kind support from the project research partners: the Commonwealth Science and Industrial Research Organisation (CSIRO), Charles Sturt University, the Bureau of Meteorology and the Australian Department of Agriculture, supported by Animal Health Australia (AHA).

Keywords: *Disease spread modelling, emergency animal disease preparedness, evidence-based policy, foot-and-mouth disease*

The development of a marine species distribution modelling approach designed for a regulatory context

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Abstract: Modern shipping relies on taking on large volumes of water to use as ballast to provide stability and manage stresses in empty vessels. Ballast water has been implicated in the translocation of invasive marine species worldwide including zebra mussel (*Dreissena polymorpha*) in the United States and the northern Pacific seastar (*Asterias amurensis*) in Tasmania among many others. Many of these species have caused extensive ecological and economic damage. In 2004 the International Maritime Organization adopted the International Convention for the Control and Management of Ship's Ballast Water and Sediments, which requires international vessels to manage their ballast water in order to mitigate the biosecurity risk. Australia has been a world leader in the management of ballast water introducing voluntary guidelines for the management of ballast water in 1990. In 1995 CSIRO was commissioned to develop a decision support system to assess the risk of ballast water uploaded from overseas ports being discharged in Australian ports and this water later adapted for domestic voyages to fulfil the requirements of the Biosecurity Act (2015).

The predicted potential range of a species is a key factor in this system for determining whether management is required. This was initially done using the Ballast Water Risk Assessment method developed by the CSIRO for the Department of Agriculture, based on life-cycle modelling. In parallel to the development of this approach, a different distribution modelling system was developed by the Department of Agriculture to estimate the maximum potential range of invasive marine species for cost-sharing purposes under the National Environmental Biosecurity Response Agreement. Species Range Mapping does not explicitly consider lifecycles, but instead compares water temperatures to a species maximum and minimum temperature tolerances.

This project was undertaken to compare the results and highlight the advantages of each approach. We found that Species Range Mapping is easier to parameterize but still produces robust results, and this makes model outputs much easier to explain to policy makers and stakeholders. The approach is similar to CLIMEX, in that it provides a framework for information from the literature on experimental and observational data to be used in conjunction with occurrence records. This makes it ideal for decision making in the case where information is sparse and risk can be directly framed in terms of the species' ability to tolerate temperature extremes, which can be difficult when using a statistical model such as MaxEnt.

Keywords: *Species distribution modelling, marine biosecurity, invasive species*

Surveillance strategies for weed eradication: Hawkweeds in Kosciuszko National Park

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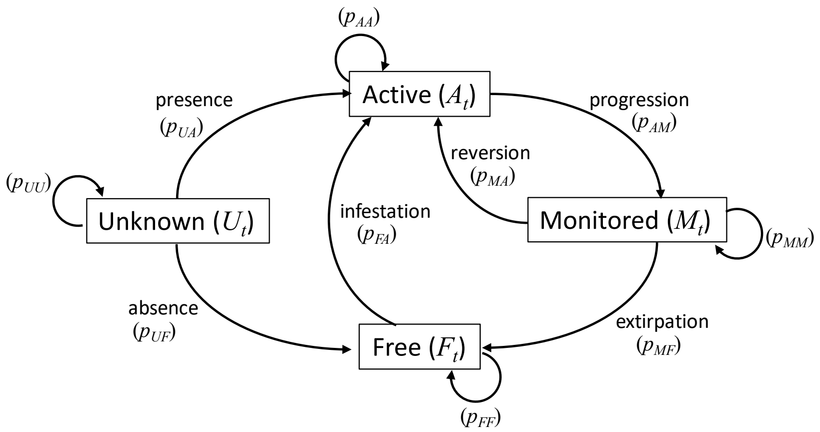
Abstract: Invasive species cost billions of dollars annually, causing damage to agriculture, the environment and the economy as a whole. Countries and states have elaborate biosecurity systems to prevent entry and spread of pests, diseases and weeds, but quarantine measures sometimes fail and incursion responses are initiated to attempt eradication of unwanted entries if feasible. The success of an eradication program ultimately depends on the ability to find pests and prevent reproduction. Search theory can help design efficient surveillance programs to contribute to eradication.

Search theory is one of the oldest areas of operations research. The basic search problem is to find an allocation of effort in space that maximises the probability of finding a target subject to a constraint on effort. This paper presents an application of search theory combined with dynamic modelling to the case of environmental weeds. Our case study for the Hawkweed eradication program in Kosciuszko National Park illustrates how research and model development can occur in close consultation with agency staff who are managing the program and conducting operations in the field.



We show why obtaining a measure of detectability is essential to develop effective tools for allocating surveillance resources. The use of detector dogs, remote sensing, drones and other tools provide new opportunities to improve eradication probability, but we need to relate their costs to their detection capacity. We develop a state-based model where sites on a map are classified as being in one of four possible states, ranging from infested to free of weeds. The final objective is for all sites to be free by distributing surveillance resources as efficiently as possible in space and time. In the model we express state-transition probabilities as functions of search effort per site. We estimate eradication feasibility based on the resources available and their allocation.

The optimal mix of methods to apply will vary across space and time depending on their relative cost and detection capacity. Those are factors that are yet to be measured and some field experiments may be needed, but the large amounts of spatial data collected routinely as part of ground operations remain largely untapped. There is potential for some parameters to be estimated from the data, and for the model to guide the collection of additional data. This approach provides a good mechanism for the results of our research models to be applied on the ground in an iterative process where the model and the program are both improved as more data are collected and processed, ultimately contributing to eradication success.

Keywords: *Invasive species, Search theory, eradication feasibility*

WeedSearch: a tool for weed eradication programs

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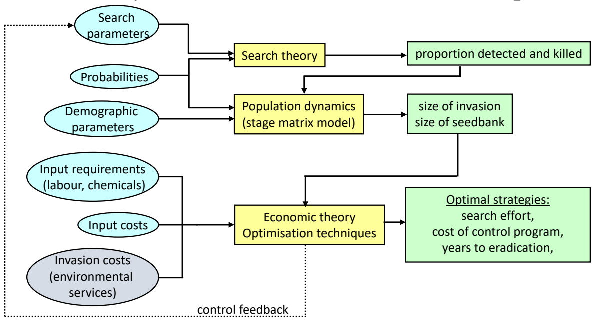
Abstract: Weeds invading natural environments are a serious problem globally, with management strategies ranging from eradication to no action depending on priority and funding. Calculating the costs and benefits of alternative weed management strategies, including eradication, requires an understanding of the 'detectability' of the pest, something not typically considered in biological invasion models. There is always a probability that organisms will be overlooked when searching, and these organisms may reproduce and contribute to spread of the invasion. Search theory (Koopman, 1980) offers an approach for relating the probability of detecting targets to the effort expended in different search environments. The key is a simple measure of detectability, which can be related to searcher ability, biological factors and the search environment (Cacho et al., 2006).

Search theory is the basis of 'WeedSearch', a spreadsheet-based tool which allows the user to calculate the probability that a weed invasion will be eradicated based on the amount of time invested in searching for it (search effort). The model is based on the paper of Cacho et al. (2006), and requires 24 input parameters, including the number of infested sites, estimated average plant density, search area, detectability, and a range of biological parameters such as seed longevity. Total search area is the primary factor that determines eradication cost.



WeedSearch provides decision-makers with evidence-based information on likely cost and duration of eradication projects, and has been used both in Australia (Panetta et al. 2011; Csurhes 2016; 2018) and overseas (Robison and Darin, 2009; Corbin et al. 2016) to predict the cost and duration of weed eradications.

In this paper we present the basic features of the Model and look at how it has been used by different groups. We also discuss potential ways in which this, and similar tools can be made more accessible to users and contribute to success in eradication efforts.

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Keywords: *Biosecurity, search theory, detectability, weed management, economic evaluation*

The role of modelling and simulation to supporting evidence-based decision making in agriculture and biosecurity: science meets policy

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Abstract: This unique session will bring together scientific researchers and policy-makers to discuss how we can best use models to support decision-making for agricultural and biosecurity policy. This slot will be used to invite a panel of experts working in the area of agriculture and biosecurity policy to lead discussion on the topic of the role that models and simulation can play to inform decision-making, both now and in the future.

Discussion will follow presentations of applied scientific research where models have been developed with the intention to support policy making, ideally with some evaluation of the role they have played in helping formulate policy/enable decision-making. We aim to arrive at insights on what benefits models can provide, and also perhaps what might hinder models from reaching their potential to assist in formulating policy.

Keywords: *Biosecurity, agriculture, policy, decision support*

Mechanistic forecasting of exotic pest establishment and spread – an integrated approach for industry preparedness

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Abstract: The establishment, spread, and impact potential of pests in exotic ranges is difficult to predict due to the frequently limited knowledge of pests prior to establishment. However, preparedness strategies for an invading species, including surveillance, mitigation, management, and extension must incorporate these processes to maximise their benefits.

Here we demonstrate an integrated approach that has been applied to two high priority exotic pest insects of Australian horticultural industries – spotted-wing drosophila (*Drosophila suzukii*) and the vegetable leafminer *(Liriomyza sativae*). The novel approach incorporates ecological drivers of pest population increase and decrease, local-spread, and human-mediated long-distance spread. A focus on physical quantities (as opposed to dimensionless risk indices) allows the joint estimation of long-term establishment potential, seasonal activity potential, rates of spread, and subsequent impact to industries in terms of predicted pest population numbers. The simulation of growth and dispersal of populations across a large heterogeneous gridded landscape is optimised to run in real-time on a laptop computer. This computational efficiency aids sensitivity analysis, parameter estimation, and general ease-of-use. Overseas data on rates of pest spread is used to validate model for use in Australia (Figure 1).

The developed approach focuses on universal biological processes (climatic ecology, population dispersal, and human-mediated impacts) contributing to a generic framework that helps reduce the need for bespoke models being developed for new pest threats. The modular nature of the framework also facilitates model simplification (e.g. excluding human-mediated spread) or model expansion (e.g. inclusion of founder effects or host-plant limitation).

Taking *D. suzukii* as an example, these model outputs have allowed us to answer diverse but interconnected management questions. Australian establishment was determined to be highly possible in the vast majority of horticultural regions. The seasonality of *D. suzukii* is markedly different across regions, pointing to the potential utility of harvest schedule modifications to limit production losses. Simulated incursions into Australian coastal cities suggest eradication programs will have limited efficacy due to rapid spread and population growth. Accumulated industry impacts will accelerate through time, but are highly dependent on the inclusion of spread processes (which are frequently ignored in impact analyses). These findings have already directed industry awareness campaigns and will continue to assist ongoing monitoring programs and the exploration of alternative management options.

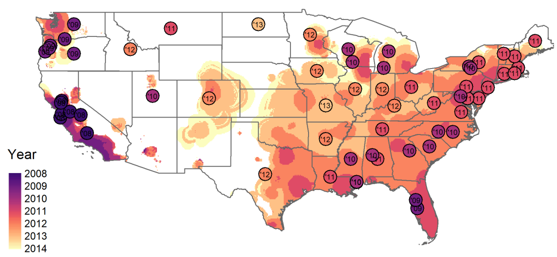

Figure 1. Model validation: predicted and observed population establishment times of *D. suzukii* in the United States. The full-model was parameterised using ecological data from the literature. Circles denote compiled distribution data, while the colour gradient outside the circles denotes the model predictions.

Keywords: *Dispersal model, mechanistic model, human-mediated spread*

Can we predict the effectiveness of a systems approach? Understanding infestation risk along commodity pathways

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Abstract: Managing horticultural pests has relied heavily on pesticide use and endpoint treatments to reduce pest populations and the rate of infestation in marketed fruit (Dominiak 2019). Growers have also relied on endpoint treatments to kill pests for export products. However, there is increasing pressure to reduce reliance on endpoint treatments that can affect fruit quality and shelf-life, e.g. methyl bromide (Fields and White 2002) and heat treatment (Hallman 2000). It has been difficult for growers and regulators to understand how infestation risk reduction is cumulative across production stages. Systems approach methods can be broadly grouped into four risk reduction objectives (van Klinken et al in prep) which seek to minimise host vulnerability, minimise exposure to the pest, reduce infestation rates, and reduce establishment likelihood.

We developed a qualitative model using a Bayesian network to predict the combined efficacy of risk reduction measures on the final packed product, for host vulnerability, risk of exposure to pests and the infestation rate at the preharvest and harvest production stages. The model can be run as scenario-based or real data can be used where acquired.

Regulators and industry bodies can run scenarios selecting different measures to control exposure to pests, such as pest exclusion using glasshouses and netting or thorough integrated pest management. They can also determine host vulnerability through the relationship between host susceptibility, A-grade fruit selection at harvest and fruit development stage at harvest. At the packhouse, infestation rate can be determined by processes chosen for killing pests (e.g. endpoint treatment or cold storage) or removing infested fruit (e.g. manual or automatic sorting). Quality assurance inspection can also be selected at the end to better determine the infestation rate of the packed product.

The model allows regulatory decision makers to assess systems approaches to determine if protocol compliance is met and whether sufficient measures have been undertaken to generate low pest exposure and/or low infestation rate. This will allow decision-makers to give informed advice related to specific areas and conditions. Industry bodies can also use the model to inform growers what is needed to design a thorough systems approach protocol.

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Keywords: *Systems approach, infestation risk, policy, horticulture, Bayesian network*

Area-wide management guidelines for Sterile Insect Technique developed through interdisciplinary modelling research

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Abstract: New technologies for insect pest management, such as Sterile Insect Technique (SIT), present an opportunity to reduce chemical use in agricultural landscapes. However, they require socio-economic and ecological evaluation to ensure they are effective. We present a decision-making framework for sterile Queensland fruit fly 'Qfly' (*Bactrocera tryoni*) release informed by both economic and biophysical models as part of an area-wide management (AWM) program with SIT. The conceptual framework presented here guided the development of economic and biophysical models to meet the objective of informing management strategies.

Our economic modelling has provided an important assessment of the feasibility and opportunities for AWM and SIT at the scale of three case study regions in southern Australia (Sunraysia, Murray/Goulburn valley (MGV) and Riverland). We found that there are three potential economically-viable implementation strategies for AWM of Qfly including SIT: outbreak eradication (and potentially maintenance of area freedom, should legislation allow); direct substitution for existing management techniques in spatially-isolated contexts (including in support of industry-specific market access); and more effective management in an urban context than existing ad hoc approaches.

In terms of releases of sterile males, our biophysical research has generated valuable risk maps for three case study regions. An understanding of the spatial and temporal risk of Qfly occurrence for a given target region is essential to the development of a future tool or system for planning sterile fly releases, as well as for ongoing management and monitoring programs. As a minimum, knowledge of the land use, climatic suitability and host phenology in a region is required. Ideally, this should incorporate the construction of risk maps that can inform decision-making for releases. The spatial simulation modelling showed that complex landscapes, containing a higher diversity of fruiting hosts across different seasons, will pose greater challenges in achieving population suppression and adoption of AWM strategies in readiness for SIT. Urban areas pose a significant challenge, as these areas provide a reservoir of flies throughout the year with potential to move into nearby crops. Therefore, it is important that they are managed as part of an AWM approach (potentially employing SIT) in order to effectively suppress flies across a landscape. The model identifies potential hotspots and bottlenecks in space and time which can be used to develop more targeted and effective SIT release strategies. We show that an urban treatment is most effective when reducing populations in late winter/early spring before they can move into the agricultural area.

Our work highlights the importance of a conceptual framework that provides a broad consideration of the economic, social, and biological feasibility of a SIT program prior to the release of sterile flies using modelling approaches, as well as an ongoing need to consider the socioeconomic and biophysical components of the system for sterile Qfly releases to be successful. This work led to the development of online guidelines for area-wide management (AWM) of Qfly incorporating Sterile Insect Technique (SIT) in Australia www.area-wide-management.com.au.

Keywords: *Bioeconomic modelling, Spatial simulation, Queensland fruit fly, Bactrocera tryoni*

A simple model for size-at-detection of an invasive species under surveillance

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Abstract: The impact of invasive species is affected by a range of factors, many of which can be anticipated in advance – for example, the prevalence of host material, climate suitability, the size of affected agriculture and so on. One factor that cannot be anticipated is the size of the incursion at the time of its detection. The impact of an incursion is tightly tied to its maturity at detection, ranging from a single seed, for example, to a 50,000 hectare infestation of plants.

We propose a simple probability model for the detection of an invasive species that can either capture or integrate out the consequent uncertainty of the maturity of the incursion. We capture the relationship between surveillance and the detection of the organism using survival analysis: the detection of the incursion is analogous to the survival event; it is a binary occurrence that happens at some point in time, and once it has happened it does not happen again.

Under such a model, we can easily connect the distribution of the size of the infestation at the time to detection to the probability of detecting the incursion given that it has not already been detected, namely, the hazard function. For example, a popular model for the detection of an incursion of size x with number of traps t and probability of detecting a single pest p is

$$h(x, t, p) = 1 - (1 - p)^{tx}.$$

Algebra leads us to a size-at-detection pdf. Other corrections are also applied as needed. The outcome is a pdf that is a function of process parameters, enabling straightforward assessment of different surveillance choices. Parameter estimates for the distribution can be derived from first principles, field experiments, or expert elicitation.

In this presentation we will derive and demonstrate the use of the survival-based incursion size at detection pdf and its implications and challenges.

Keywords: *Surveillance, invasive species, survival analysis*

Modelling the population dynamics of green mirids to support IPM decision-making for the Australian cotton industry

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Abstract: The green mirid (*Creontiades dilutus*) is an important pest species for the Australian cotton industry, damaging bolls and reducing lint and fibre quality. Populations of the green mirid were initially controlled indirectly through the use of insecticides targeting *Helicoverpa* spp. Subsequently, the introduction of transgenic cotton varieties (e.g. Bollgard II® cultivars) decreased the need to use chemical pesticides to manage populations of these heliothine moths, resulting in a subsequent increase in the presence and impacts of green mirids in cotton fields. Current options to control green mirids rely heavily on the use of broad-spectrum insecticides, which are known to have negative impacts on beneficial insects. Integrated pest management (IPM) programs have been implemented to limit the use of chemical pesticides to limit the development of resistance by basing spray decisions on the level of damage observed on the plants and the abundance of the insect. While damage on the plants can be assessed relatively easily, monitoring the number of green mirids can be demanding and requires regular surveillance over a prolonged period during the cotton growing season. Green mirids are highly mobile and can develop from eggs to adults within 15 days, with the potential for rapid increase in abundance. Consultations with the cotton industry around Narrabri revealed that the green mirid is a high impact pest, and that forecasts of phenology and abundance could be highly valuable to producers to help them manage the pest impacts.

The objective of this study was to develop a process-based model to accurately simulate the phenology and relative abundance of green mirids across a fine-scale lattice spanning the 13 cotton regions of Australia. Our simulation model was built using the DYMEX software package (www.hearne.software). The initial model was built using insights gained from published laboratory experiments on green mirids, supplemented where necessary with theoretically-derived functions and parameters. The resulting model describes how different environmental processes influence each of the life stages of the green mirid. It explicitly incorporates the causal structure of the system; where the species is represented as a set of behavioural, morphological, and physiological processes that respond to external factors including weather and food resources. The discrete-time model operates on a daily time-step, using commonly-available weather data.

The simulations can provide a powerful tool for cotton agronomists and growers to get an early warning of the population dynamics of the green mirids and potential forecast scenarios. This information can be used to target field scouting and can be used to evaluate management options as the population numbers approach the IPM thresholds.

Keywords: *Agricultural pest species, Creontiades dilutus phenology, DYMEX, population dynamic, process-based model*

Modelling the impacts of consumer policies on organic farming adoption: Ecological and sociological perspectives

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Abstract: Food production tends to keep growing to meet human nutritional needs. Expanding conversion of natural habitat to agricultural land is the main driver of global forest loss and species extinction. According to the 2019 Intergovernmental Panel on Climate Change report, an essential part of reversing losses and avoiding ecosystem collapse is transitioning into organic food production. Organic food has significant environmental and health benefits, decreasing the toxicity of agricultural production, improving soil quality, and overall resilience of farming. Despite the recorded 20% growth in organically managed farmland, their global land area is still far less than expected, only about 1.4%.

While organic farming provides a more sustainable solution to some of the ecological challenges in agriculture, it usually produces lower crop yields in comparison to their conventional counterparts, which results in higher food prices. Consumer food preferences and choices can be the turning point factor, where higher interest for organic diets can motivate farmers to adopt organic farming practices. Increasing consumers' demand for organic food not only increases the rate of organic farming adoption but also improves the farmers' perceptions of risk and risk management strategies.

In our research, we focus on this consumer-centric approach as a pathway in the transition towards sustainable food systems. We develop an extended supply chain model for organic versus conventional agro-food products where a hybrid pull-push system controls the operations. Systems architecture and integrated modelling approaches help us to simulate the patterns of organic and conventional wine consumption-production by linking the consumption sub model to the agricultural production and supply chain models.

We take the wine sector as an example to calibrate and validate the model for the case study of Australia. We assess the effectiveness of different policies, such as raising consumers' organic knowledge and increasing tax on less environmentally friendly wines to change consumers' preferences. This research provides important policy implications for decision-makers in the food sector to understand the effect of various interventions on behavioural changes and actions of consumers. It can also help businesses in understanding the behavior of customers and making informed decisions about organic production and its' future opportunities.

Keywords: *Sustainable supply chain, complex systems, environmental behavior, agricultural economics, policy measures*

Computational modelling of estimating the long-distance dispersal threat of pests and pathogens from Southeast Asia to Australia

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Abstract: Computational modelling has proven to be a valuable tool to study the dynamics of biological systems at both spatial and temporal scales. Such a tool can generate new insights into phenomena or problems that cannot be observed or otherwise explained. Atmospheric dispersal of pest organisms is considered a potential pathway for entry of pathogens and arthropod pests into Australia, and of significant potential threat to agriculture. However, there are few studies considering the invasion threats to arable lands. Due to the inherent complexity of long-distance aerial dispersal (LAD) driven by both abiotic and biotic factors, it can be challenging to identify any spatio-temporal dynamics of such dispersal patterns. The interplay of these factors can be stochastic and lead to a large degree of uncertainty in the dispersal patterns.

Effective and efficient pest surveillance requires a general understanding of these dispersal patterns at different spatial and temporal scales. Similarly, investment decisions in Northern Australian agriculture should be cognisant of the pest threats from our northern neighbours. Further, agricultural endeavours in the north could provide a stepping-stone for invasion of agricultural areas further to the south. A better understanding the consequences of these will improve pest management, thereby supporting decision-making for agricultural and biosecurity policy, thus bringing economic benefits to farmers and orchardists. In addition to traditional experimental approaches, mechanistic simulation modelling of spatio-temporal dynamics of pest threats from LAD is crucial to this endeavour.

In the current study, we used computational modelling of LAD to Australia, and demonstrated the subsequent threat to Australian crop zones (arable lands) from fungal pathogens. Several neighbouring land masses to Australia were identified as putative source sites. Hybrid Single-Particle Lagrangian Integrated Trajectory model (HYSPLIT) was used to run the computational modelling simulations. HYSPLIT has been widely used for predicting the trajectories of particles and subsequent dispersal patterns in a number of fields.

This study identified where, when and how pest invasion may occur and also demonstrated the spatio-temporal dynamics of dispersal patterns from putative source sites. From a biosecurity perspective, the accurate predictions of pathways and infested areas of pest organisms will aid in eradicating the invasive pests by taking early intervention activities. More importantly, our study demonstrated that the spatio-temporal dynamics of dispersal patterns varied in terms of the different sizes of fungal spores (i.e. their aerodynamic diameters). This will help decision-makers to narrow down potential species from the putative source locations that might arrive in Australia in certain time and locations. The identification of the sources of pest organisms will allow us to know more about alien species such as their physiology, behaviour and ecology, thereby developing the most suitable control methods for targeted species. In summary, the results showed that the threat to arable lands varies between seasons and years and these results could have implications for future biosecurity surveillance programs both at the farm, state or federal level.

Keywords: *Invasive ecology, Hybrid Single-Particle Lagrangian Integrated Trajectory model (HYSPLIT), wind dispersal modelling, pest risk assessment, decision-making pest management*

Assessing the cumulative impacts of mining activities on stygofauna across the Pilbara region

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Abstract: The Pilbara region is a global hotspot of diversity for stygofauna: invertebrates living exclusively within the groundwater. The apparent congruence of unique and diverse stygofauna assemblages with areas of high mineral value has created challenges for both mining developments and the conservation of stygofauna diversity. Mining often requires groundwater abstraction, which can markedly alter or remove stygofauna habitat across large areas. Compounding these issues has been the major shortfalls in our knowledge of stygofauna, including uncertainty over the taxonomy of surveyed animals, ongoing species discovery, highly variable assemblages resulting from surveys in the same location, and bias in the distribution of surveyed locations. Environmental assessments have largely relied directly on survey data, which has resulted in substantial uncertainty as to the likely impacts of proposed mining developments on stygofauna diversity.

Here we report on a collaborative research project between CSIRO and BHP that aimed to dramatically improve our understanding of, and ability to predict, current spatial patterns in stygofauna diversity in the Pilbara region, as a basis for better informed conservation, management and development decisions.

To achieve this objective, we took a community-level biodiversity modelling approach, developing new analytical techniques to account for the uncertainties in stygofauna survey data. Our approach included a number of major research components, including: collating and standardising all available biological survey data; deriving and assembling fine resolution layers representing subterranean habitat features; developing and applying new techniques to model diversity patterns for stygofauna, and; harnessing these models to assess areas of biodiversity significance and likely cumulative impacts of mining activities.

This research identified important drivers of stygofauna diversity patterns in the Pilbara, primarily groundwater and geological attributes. The fine resolution (≈ 30 m) maps of diversity patterns enabled us to identify likely areas of biodiversity significance for stygofauna, with the central region of the Hamersley Range possessing the highest value. We demonstrate how these spatial biodiversity models can be used to support assessments of the impacts of proposed mining developments on stygofauna.

We further harnessed our spatial biodiversity models to assess the cumulative impacts of all past, present and likely future mining activities on the persistence of stygofauna diversity across the whole Pilbara region. This analysis found that despite high congruence of areas of importance for both mining and stygofauna diversity, the cumulative impacts of mining activities to date on the persistence of stygofauna are relatively low.

Our fine resolution biodiversity projections provide a new capacity to help inform decision making associated with conserving stygofauna diversity amidst increasing disturbance of belowground environments. These models and projections can be used to assess likely implications of proposed mining developments, and identify development scenarios that reduce the likely impacts on stygofauna diversity. The knowledge and techniques we developed can therefore help reduce the uncertainty in assessing impacts of mining activities on stygofauna and improve the management of these unique species.

Keywords: *Biodiversity, conservation, composition, species, groundwater*

Spatial comparison of biodiversity with sources of hydrological stress in the Murray Darling Basin

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Abstract: The Murray Darling Basin Plan was originally agreed in 2012, and as of late 2019 is close to being fully implemented. One of the central features of the Plan is to reduce anthropogenic diversions of water within the basin and to return water to waterways for environmental purposes. While this has been broadly successful to date, much of the emphasis has been on the major waterways downstream of the larger on-stream dams.

A similar emphasis on large on-stream dams exists in the international scientific literature. There are many papers covering all aspects of environmental water management in major waterways downstream of large in-stream or floodplain structures, whether they be weirs, dams, or levees. By comparison, there fewer papers examining issues around environmental water policy and management in smaller streams where the impacts of small-scale assets and catchment processes dominate, recognising that it is very common for waterways to be impacted by catchment features and processes that are distant from the stream network.

Is this focus on environmental flow management downstream of large on-stream dams misplaced? Or is it demonstrably efficient in protecting and/or restoring a significant proportion of the biodiversity in a catchment? This presentation will outline some recent work which has shed some light on these questions. This study attempts to identify where biodiversity is present in the Murray Darling Basin, and whether this coincides with areas where various types of anthropogenic flow stress are present.

Measures of biodiversity are spatially overlayed with measures of hydrologic stress across the Murray Darling Basin. Biodiversity is represented by spatial data showing aquatic ecosystem types and extents, fish presence data, and threatened species presence data. Hydrologic stress is approximated using the ratio of storage capacity to mean annual flow ("degree of regulation"), along with locations of all man-made storages from small stock dams to major irrigation dams. This analysis reveals that:

- Hydrological stress caused by regulation is very significant, but in some local areas this is outstripped by the stress caused by catchment interception by small runoff dams. This suggests that, in some locations, management of interception activities might provide more significant environmental benefits than management of large regulating storages.
- Unregulated streams in the Murray Darling Basin hold the majority of the biodiversity in the basin despite some of these streams having a very high degree of regulation, suggesting that there may be some opportunity to improve environmental outcomes for the basin as a whole through improved management of these streams.

Clearly, this has significant implications for the Murray Darling Basin in terms of where investment decisions in water management and recovery are focused within catchments. While management of environmental flows downstream of major dams has been shown to be effective, in some locations it may be possible to further improve environmental outcomes through more active management of unregulated waterways and catchments as well.

Keywords: *Environmental water, farm dams, runoff dams, plantations, aquatic ecosystems*

Assessing change in regional communities as a consequence of water recovery: Issues of scale and zoning when combining data

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Abstract: The Data Integration Partnership for Australia (DIPA) is a whole-of-government initiative to make better use of existing public data. Here we present research, undertaken as part of the DIPA, into the impact on regional communities in the southern Murray–Darling Basin of water recovery for environmental use. The focus of this presentation is the difficulties and limitations of analysis conducted with data reported at varying spatial units.

The first part of the assessment of impact used publicly-available census data in calculating a community's adaptive capacity index (ACI) and change between 2011 and 2016. The ACI was calculated using Australian Statistical Geography Standard Statistical Area Level 1 (SA1) spatial units and then applied to southern Basin communities previously defined by the Murray–Darling Basin Authority. This was done as weighted means of the SA1's intersecting each region, using population-based correspondence tables. How these communities are spatially defined affects the reporting of changes to them, and therefore the potential for impact. The process of aggregating the index from SA1 spatial units to community boundaries to model how a community's change in adaptive capacity relates to reported net reductions in water availability provides one example of the issues of scale and zoning.

The second component of the analysis was conducted in the Australian Bureau of Statistics' DataLab – a secure, access-limited, virtual analysis environment. The ABS DataLab contains collections of Commonwealth data; the Multi-Agency Data Integration Project (MADIP) and Business Longitudinal Analysis Data Environment (BLADE) which include datasets from:

- Australian Bureau of Statistics
- Australian Taxation Office
- Department of Education and Training
- Department of Health
- Department of Human Services
- Department of Social Services.

We undertook multivariate linear regression modelling to explore the relationship between BLADE datasets and indicators of water availability (flow, volume, diversions and precipitation). This provides an example of analysis complicated by the multiple scales and zoning for which environmental, economic and social data are collected and reported. For instance, the reported number of agricultural, forestry and fishing businesses and business income data is located by postcode while irrigation diversions are reported by Surface Water Sustainable Diversion Limit Resource Units. Improved matching of the spatial units used in reporting socio-economic and water availability data is likely to improve the reliability of the analysis undertaken.

The use of datasets outside of their original purpose of collection requires consideration of the spatial context of the collection, as findings of analyses can be contestable. Matters of privacy, especially concerning sensitive government datasets and commercial interests, may mean the scale and zoning issues encountered in this exploratory impact analysis challenge the use of existing public data for assessments. Addressing the spatial unit issues when designing future data collections and reporting frameworks can go a long way to improving the value of the data and reliability of analysis.

Keywords: *Impact assessment, environmental water policy, spatial data analysis*

Integrated approach for predicting impacts of future climate and land use changes on macroinvertebrates in a Mediterranean catchment using GF, SWAT and HEA models

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Abstract: Climate and land use changes are expected to alter flow and nutrient regimes in catchments affecting stream habitats and aquatic biodiversity. Scenario analysis by an integrated modelling approach may assist to better understand after-effects of such projected changes on biodiversity. This study aimed to quantify the impacts of climate and land use changes on the macroinvertebrate community of the Torrens river catchments, South Australia. Gradient forest (GF) determined average seasonal flow as main factor affecting macroinvertebrate assemblages in this catchment. A catchment model developed by the Soil and Water Assessment Tool (SWAT) was used to simulate flow under following scenarios: 1) future climate change scenario (RCP 8.5) based on six global circulation models, 2) hypothetical land use change scenario of deforestation over the next 30 years, and 3) scenario combining land use and climate change. Results of the future climate change scenario suggested decreased monthly flow due to declining precipitation and increasing air temperature, in contrast to the future land use change scenario of deforestation that predicted increased monthly flows. The combined future scenario to some extent suggested a trade-off between projected climate and land use changes but indicated dominating land use impacts due to deforestation resulting in increased runoff and higher flows. The Hybrid Evolutionary Algorithm (HEA) was used to model flow-driven abundances of GF-identified key species *Hydrobiidae* spp. and *Tasmanocoenis tillyardi* over 14 years at a representative stream site. The coefficients of determination r^2 of the HEA models ranged between 0.88 and 0.96. Results indicated *Hydrobiidae* spp. to be tolerant and adaptive to altered high flows under the future combined scenario by showing higher abundance as compared to individual climate change and land use change scenarios. In contrast, *T. tillyardi* has shown affinity to low flow conditions and decreased abundance in future combined scenario. The integrated modelling approach based on SWAT and HEA proved to be suitable for studying stream health under the impact of projected future climate and land uses.

Keywords: *Climate change, land use change, gradient forest, SWAT, HEA, macroinvertebrates*

Development of the Floodplain Ecological Response Model (FERM)

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Abstract: Many countries have realised the importance of well managed environmental flows in protecting, restoring and maintaining healthy river networks and freshwater ecosystems. Environmental water management benefits from an objective method to understand how change in flow characteristics can affect flood-dependent ecosystems and the organisms within them. The quantification of ecological response to flooding provides robust and defensible measures to assess ecological benefits and sets tangible metrics to evaluate outcomes associated with different watering scenarios.

Here we introduce the innovative Floodplain Ecological Response Model (FERM). FERM is a generic conceptual model which uses infinitely differentiable functions that have derivatives of all orders everywhere in their domain to represent the continuous response of ecological targets to wetting and drying on the floodplain. Learning from and moving beyond the binary indicators and step-change preference curves that are currently widely used to underpin policy, the FERM models a completely smooth response curve and is designed to more closely imitate natural processes. The functions are developed based on hypothesis and existing knowledge of response to flow conditions, sometimes in the form of a preference curve and verified using available data. The condition of the ecological target is denoted by a score on a scale of 0 to 1. The condition score is calculated as a function of a wet or dry spell duration taking into account the initial condition of the target and whether it is on a declining or recovery trajectory.

Unlike data dependent regression models, the parameters of the underlying functions are physically-based and therefore can be parameterised using expert knowledge as well as calibrated using observed/remote sensing data. We consider it suitable to apply in data scarce regions to provide estimates with improved robustness, and easy to refine to include more processes as data become available, as demonstrated with an inclusion of a distance weighting in the case study to represent a groundwater element.

The model was developed and optimised to simulate outcomes for multiple vegetation species on large floodplains taking flood inundation extents as input from flood inundation models. However, it can also be applied to simulate a single species or guild that is sensitive to flooding using a time series of wet and dry spells.

The model can be used to test scientific hypothesis and enhanced with improved knowledge. Here we demonstrate the model using response functions for river red gum forests. The plots in Fig. 1 illustrate the response curves under wet and dry spells as well as a long-term simulation at a particular location.

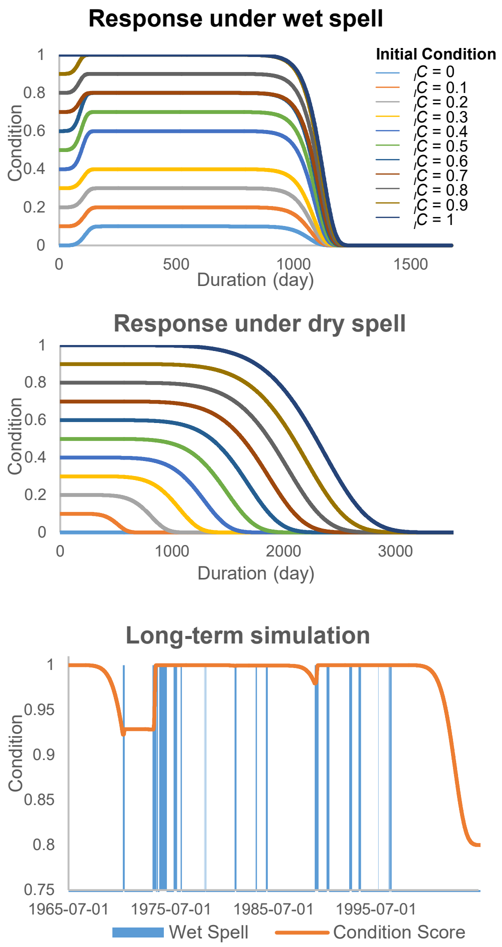

Figure 1. The response of the river red gum forest under wet and dry spells modelled by FERM and how the condition of an example grid cell (identified as river red gum forest)

Keywords: *Environmental flow, ecological modelling, flood inundation modelling*

Conceptualising River Red Gum ecological response in river basin model

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Abstract: Environmental flow optimisation models typically try to achieve flow outcomes (minimum flow limits, maximum flow limits and mimicking natural flows) with little consideration to multiple ecological objectives and asset based solutions (Driver et al., 2013; Horne et al., 2016). Although model development has seen a shift towards objectives which consider ecosystem health (Barbour et al., 2011) (Merritt, 2015) barriers still remain with respect to dynamic operational objectives based on feedback of ecological responses.

WATHNET5 is a water resource modelling program that can simulate, optimize and calibrate water resource systems. Of particular interest is the multi-objective optimization capability in WATHNET5 which is currently utilised by the urban water sector to develop water resource management strategies for urban water supply. Our long-term goal is to develop a WATHNET5 model of the Macquarie Valley to simulate real-time feedback of ecological responses for the determination of management strategies for environmental flow releases and to use multi-objective optimization to explore optimal trade-offs.

River Red Gum (*E. camaldulensis*) (RRG) ecosystems occur along river banks and in flood plains throughout Australia, including in the Macquarie Marshes. RRG ecosystems are associated with wetland health with tree condition strongly linked to flow regimes (Catelotti et al., 2015). The primary objective of this study was to develop a conceptual model of a RRG dominant ecosystem (Patch E, Macquarie Marshes) which simulates RRG condition as a function of water and climate history.

The conceptual model was developed in alignment with understanding of RRG ecophysiological mechanisms. Key insights from the literature review established that Patch leaf area can be used to represent Patch condition with strong correlation to transpiration capacity. The model incorporates RRG ecophysiological mechanisms which drive transpiration capacity using model components to simulate evapotranspiration demands and responses to infiltration and groundwater storage. Patch leaf area was characterized using remotely-sensed Seasonal Fractional Coverage (SFC) data.

The model was calibrated to correlate SFC with transpiration capacity. Patch inundation hydrodynamics were also calibrated to results of an existing 2D-hydrodynamic model of the marshes (Sandi et al. 2018). The calibration model results are shown in Figure 1 which presents a time series of simulated SFC and remotely-sensed SFC. The calibrations to SFC and Patch volume had Nash-Sutcliffe efficiencies of 0.693 and 0.844 respectively. These results suggest the conceptual eco-hydrodynamic model can provide a credible estimate of RRG condition using the history of climate and inflows to the wetlands. This positive result paves the way to explore managing ecological response by optimizing water management decisions and exploring trade-offs.

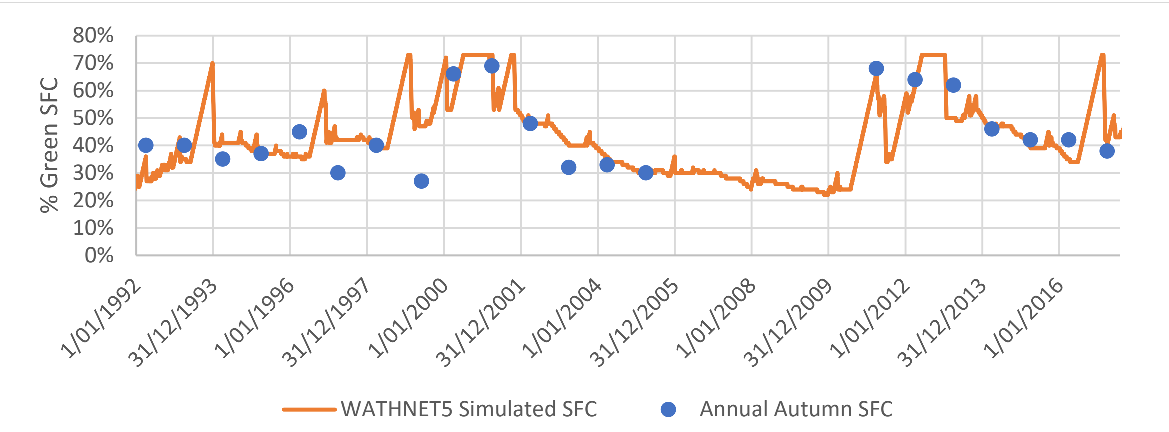

Figure 1. SFC calibration results for River Red Gum Patch E

Keywords: *Decision support, multi-objective optimisation, ecological response, River Red Gum*

Cumulative impact assessment: Accumulated lessons from a large study assessing impacts of coal resource development on water-dependent assets

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Abstract: Impact assessments seek to ensure that the potential environmental, economic and social impacts of a development or project, both beneficial and adverse, are actively considered in the regulatory or decision-making process. There is a growing imperative to consider potential stressors emanating from that development within the context of other system stressors, and ensure that the system is managed for the combined or cumulative impact, given that is what is experienced. Cumulative impact analyses remain challenging undertakings. The magnitude and complexity of the coupled human and ecological system within which developments occur make it difficult to ensure that all important system components and interactions are included, that scales are appropriate, and that predictive uncertainties are adequately propagated through the quantitative models and impact analyses.

Bioregional Assessments www.bioregionalassessments.gov.au (BA) were a major program of work, and collaboration between the Department of Environment and Energy, the Bureau of Meteorology, CSIRO and Geoscience Australia, that sought to increase the available science for decision making associated with the impacts of coal seam gas and coal mining development on water resources and water-dependent assets. They focused on Eastern Australia, and produced regional cumulative impact assessments for regions such as the Galilee, Hunter and the Namoi. The assessments undertaken were a particular type of cumulative impact assessment. They were cumulative in the coal resource developments (i.e. multiple coal resource developments were considered simultaneously), held other industries such as agriculture fixed, and were primarily a comparison between two coal resource development futures - one a continuation of the existing coal resource development, and the other with those developments supplemented by the suite of additional coal resource developments considered most likely in that region.

BA needed to balance constraints imposed by the study objectives and resources, the complexity and scale of the regions, and good practice in risk assessment. Through associated design choices and the outcomes of the assessments, a range of important lessons relevant to future cumulative impact assessments were identified. BA emphasised that trade-offs need to be made between the complexity of components and interactions, and the ability to quantify the predictive uncertainty. Overly complex models may actually prohibit appropriate uncertainty analyses. The choice of what to fix and what to consider as part of the scenarios is an important consideration. From BA we would contend that it makes sense to fix those factors related to human decisions (e.g. coal resource development) and include those factors that cannot be controlled (e.g. climate) in the uncertainty analyses. Attribution is not possible unless it can be assessed through alternative scenarios. With the comparison of two coal resource development futures, the contribution of individual coal resource developments typically cannot be isolated. Understanding the natural variability under the baseline is a key factor in putting any change in context. Scale differences are challenging (e.g. between regional and local hydrological models) and are ideally addressed by nesting those models. The structured use of expert opinion can fill data gaps and underpin models in data poor situations. For instance, expert opinion was used to translate the potential hydrological change into possible ecosystem change, and became a vital part of the modelling chain for assessing impact. Bioregional assessments continually sought to focus effort where impacts were larger, e.g. through a dedicated hazard analysis or by ruling out areas where risks were negligible.

Some of the lessons in cumulative impact analysis are being actively taken up through the Geological and Bioregional Assessment program, which is assessing the impacts of potential shale and tight gas development in three regions in Australia.

Keywords: *Cumulative impact assessment, risk analysis, uncertainty quantification, hydrological change, Bioregional Assessments, Geological Bioregional Assessments*

Freely accessible environmental modelling platforms

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Abstract: Accessibility of modelling and analysis tools beyond the academy is important across modelling and computational research domains. Cloud based systems are important for such processes, but are often not free, and do not readily address the issues of data discovery and access.

Biodiversity is one example application domain for modelling. We are in the sixth mass extinction event in Earth's history, with key threatening processes such as climate change and land use and land cover change operating at a global scale, and thus needing to be modelled across regional scales at least. However, it is unusual for conservation practitioners to have either or both of access to computational resources and the modelling skills to use them to full effect.

Two platforms have been recently developed to provide such access: The Biodiversity and Climate Change Virtual Laboratory (BCCVL) and Ecocloud. Both are substantial collaborative projects involving multiple universities and research support organisations, with primary funding from the Australian Research Data Commons (ARDC) and its antecedent organisations. Both are open source projects that are freely accessible to anyone, and provide access to algorithms and data supported by a high performance computing back-end.

The BCCVL (https://bccvl.org.au) provides a "one stop modelling shop" for the analysis of biodiversity and climate change. It provides an easy to use, web based interface to seventeen species distribution modelling algorithms, including terrestrial, marine and aquatic environments, and supports the projection of these results into the future under nine different potential emissions scenarios (Hallgren et al. 2015). Secondary analysis types support the identification of hotspots of endemic species, combination of SDM results from different algorithms using ensemble methods, species trait and migratory species analyses. All of this is supported by a range of visualisations and performance metrics. Many essential data sets are provided, with support for users to upload their own and tools to access them from online providers such as the Atlas of Living Australia (http://ala.org.au) and the Global Biodiversity Information Facility (http://gbif.org).

The Ecocloud (https://ecocloud.org.au) is a broader project that allows more advanced users to work "closer to the metal". It provides access to virtual desktops (CoESRA) and interactive coding environments (Jupyter notebooks supporting both Python and RStudio) with greater resources than the average desktop machine due to direct access to the high performance computing back-end. A key part of the Ecocloud is its Data Explorer. This provides a search interface across a wide range of environmental data providers for Australia, with more than 47,000 data sets indexed at the time of writing. The system provides code snippets to make loading of these data sets a simple copy-and-paste exercise.

Platforms like the BCCVL and Ecocloud are an important step forward to make modelling research available to non-researchers. They remove a large part of the learning curve needed to implement and models and analytical tools, while also providing the resources to operate on realistically sized data sets relevant to practical applications.

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Keywords: *Biodiversity, Environmental data analysis, Ecocloud, BCCVL*

Spatial modelling shows that permanent drink sites influence the predicted suitability of nest sites for a mobile species in a water limited ecosystem

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Abstract: Many animals in Australia depend on hollow-bearing trees for habitat, and hollows can take up to 170 years to form naturally. The forest red-tailed black cockatoo (*Calyptorhynchus banksii naso;* FRTBC) is a wide-ranging subspecies that inhabits the multiple-use jarrah forest of Western Australia and requires hollow-bearing trees in species such as the jarrah (*Eucalyptus marginata*) and (*Corymbia calophylla*) for nesting. Habitat loss due to mining, agriculture and development has reduced the extent of the forest by approximately seven percent since 1989, while a drying climate has altered the FRTBC's range and the resources that it depends on.

We surveyed 98km^2 of the northern jarrah forest and recorded the presence of confirmed nesting sites. We collated a total of 86 response variables to assess causal relationships between the selection of nest sites by the FRTBC and the environment. These data comprised topographic data, such as relative elevation and aspect, soil composition data, such as available nitrogen and soil available water content, climatological data, such as precipitation and wind speed, and remotely sensed data from the Landsat and Sentinel missions. It was hypothesised that the proximity of hollows to drink sites would significantly affect the suitability of sites across the forest. Thus, we conducted additional surveys to locate drink sites utilised by the FRTBC, and calculated the distance from these drink sites to every nesting site. All data were generalised to 30x30m resolutions for the purpose of statistical analysis. We performed a forward subset selection using Bayesian information criterion (BIC) to determine the most parsimonious set of predictors that explained the most variance in our data. Following this, we spatially modelled and predicted suitable nesting sites across the study area with generalized additive and classification tree models. In order to test the sensitivity and specificity of our models we surveyed an additional 36 independent sites with varying rainfall regimes and predicted suitability thresholds, and generated receiver-operator curves for our predictions.

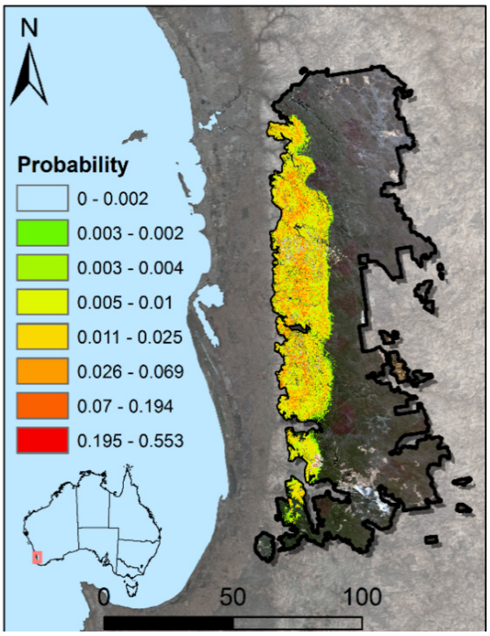

Figure 1. The results from generalized additive models of nest site suitability across the northern jarrah forest.

Our results indicate that suitable hollows are generally found amongst stands taller than 10m, lower in the landscapes, in higher rainfall areas and in productive areas of the forest, while the proximity of permanent drink sites significantly altered the occurrence probability of nest sites and improved model results. Determining FRTBC nest site occurrence for the northern jarrah forest, as well as how the availability of water interacts spatially with nest site suitability, will aid in the adaptive management of this subspecies and potentially mitigate the human impact on critical FRTBC habitat. Furthermore, this study highlights the differences between linear and tree based methods for terms of forestry and biodiversity management.

Keywords: *Environmental modelling, geospatial analysis, GIS, remote sensing*

EXTENDED ABSTRACT ONLY

Highly precise terrain models expose soil pattern based on sub-meter elevation detail

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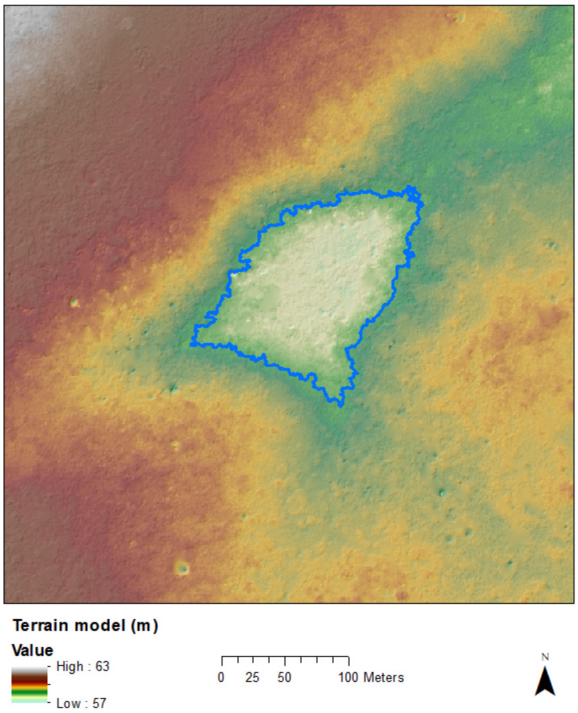
Abstract: Detailed soil information is critical to assess the future of our natural assets. Global agribusiness is a multi-trillion-dollar industry with the need to grow with population increase. Detailed soil information is vital for economic optimization on farms (fertilizer and herbicides are costly, and minimization needs spatial intelligence) as well as for land management, policy development and planning.

Topography is a key soil forming factor. High-resolution airborne photography has developed rapidly during the last decade, allowing image mosaicking and terrain modelling at unprecedented extent and accuracy. Modern, low cost computers allow 3D processing of these data sources, ensuring potential for wide adoption of ultra-precise terrain analysis.

Photogrammetric stitching was performed on 13,300 36 Megapixel images using AGISOFT Photoscan Professional, resulting in a point cloud of 6.4 trillion points. A terrain model was produced at 30cm pixel size and an orthophoto was derived using the native resolution in the raw imagery (5cm) with an extent in excess of 300,000 x 700,000 pixels.

Visual interpretation of the air photo mosaic with terrain shows marked correspondence between soil colour and vegetation pattern. These can be related to intricate differences in soil and water confluence, arising from sub-meter differences in terrain height (the blue line shows the 58.4 m contour line, approximating the extent of a local depression with a depth of ~39 cm). The study demonstrates influence of small topographic variation on water flow, soil development, and vegetation pattern and suggest an objective means of detailed landscape segmentation for biological surveys and wildlife monitoring.



Keywords: *Terrain modelling, soil forming factors, digital soil mapping*

Machine learning-based surface air temperature estimation using multiple source of predictors in Tibetan Plateau, China

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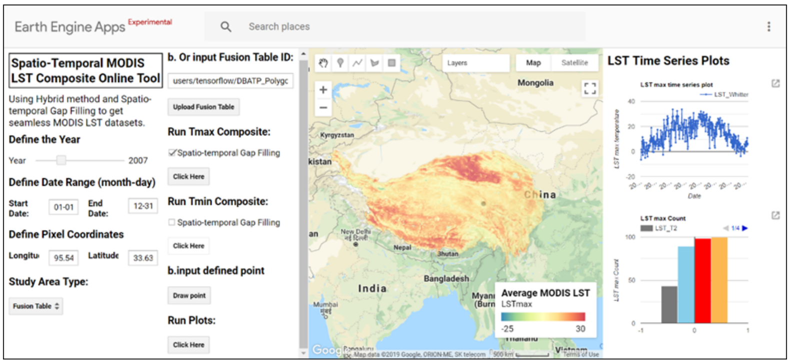
Abstract: The surface temperature lapse rate, which is differs by elevation, has a substantial influence on the accuracy of traditional geospatial interpolation methods. The spatial distribution of meteorological stations is quite sparse in Tibetan Plateau (TP). In addition, most of the meteorological stations are located at relatively low elevations (<4000 m) in the south eastern part of the plateau. This leads to an issue in geospatial interpolation for mountain climate studies. Thus, it is important to estimate meteorological elements (radiation, temperature) related to thermal conditions in high-altitude plateau using alternative information.

In this study, new methods such as advanced machine learning with remotely sensed datasets are used to estimate surface air temperature in the Tibetan Plateau. Daily observed surface air temperature data were obtained for the period 2003-2013 from 130 climate stations. Multiple sources of predictors, including incoming solar radiation, geographic locations and biophysical factors, were used to predict surface air temperature. We used four representative and popular Machine Learning algorithms, Random Forest (RF), eXtreme Gradient Boosting (XGBoost), Support Vector Machine (SVM), and Multivariate Adaptive Regression Splines (Earth). We employed 10-fold Leave-Location-Out cross validation to examine the performances of Machine Learning algorithms. The results indicated that the XGBoost algorithms outperformed other three algorithms in estimating daily temperature. Furthermore, the R^2 and RMSE in monthly surface air temperature estimation generally fall in the range of 0.90-0.95 and 1-2°C. Given the complex terrain, climate conditions and high elevations on the Tibetan Plateau, the performance was acceptable. In addition, we developed an online app to provide continuous daily maximum and minimum land surface temperature datasets at 1km resolution for 2002-2019. With this tool, it not only gave us instant access to a global-scale LST data archive, but also provided site-based MODIS minimum and maximum LST time series data. Monthly surface air temperature datasets derived from XGBoost algorithms from 2003 to 2013 were used to explore the warming or cooling trend across Tibetan Plateau. We found that most of the warming trend was in the elevation range between 3 km and 5 km. As a comparison, the summit above 6 km in Kunlun Mountains and Himalayas Mountains exhibited a cooling trend.



Machine Learning models do show obvious advantages in the area with sparse meteorological stations, especially for the high-elevation area of Tibetan Plateau. Solar radiation and vegetation indices are also related to spatial variability in near-surface air temperature, whereas MODIS LST is more strongly related to temporal variation in surface air temperature.

Keywords: *MODIS LST, Machine Learning, surface air temperature, Tibetan Plateau, climate change*

Accuracy analysis in CH4MODwetland simulating CH4 emissions from Chinese wetlands

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Abstract: Accuracy analysis of a process-based model is important to evaluate the reliability of the model estimates at different wetland. In this study, we analyzed the three sources of the root mean square error (RMSE) a process-based model ($CH4MOD_{wetland}$) in simulating CH_4 emissions from different wetlands sites and types in China. The result showed that the RMSE sources are different among the wetland sites, but at most of the sites, the random sources of error measures a large quantity. The model can explain 70%, 54% and 77% of the variability in the daily CH_4 fluxes from peatland. Although the RMSE was 129.5% and 71.2% for the simulation at coastal wetland sites and marsh sites, over 90% of the errors were come from the random error. For the peatland sites, the RMSE was 47.9%, with 70% contributed by the random error and 23% by the regression error. The simulated seasonal CH_4 emissions matched quite well with the observed values for coastal wetlands and peatland but showed a little underestimation for the marsh. The main contributor to RMSE in simulating seasonal CH_4 emissions is the random disturbance, which account for 76.97%, 74.05% and 84.12% for the peatland, marsh and costal wetland, respectively. The study indicated that although the random error is the main contributor of RMSE, we should still make effort on improving the model mechanism and make more detailed parametrization in order to reduce the non-random errors.

Keywords: *CH4MOD-wetland model, accuracy analysis, CH4 emissions*

A framework for the generalised computational modelling of various hazards in geospatially situated social systems

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Abstract: Paracelsus argued that poisons are thus defined due to the consequences of the degree of exposure to any substance, and not the fact of exposure itself, which has led to the apocryphal but highly apt quote "the dose maketh the poison". Nevertheless, the conceptualisation of hazards in the context of toxicology, occupational and environmental medicine, and risk management has resulted in the adoption of well-accepted but simplified systems for defining different types of hazards. Examples of these include the Chemical, Biological, Radiological, Nuclear and Explosive (CBRNE) hazard framework in first response settings, and the Physical, Biological, Chemical, Ergonomic and Psychosocial hazard framework in occupational medicine and safety science. Nearly all exposures, however, are more complex than simple categorization would imply and present hazards to humans in multiple simultaneous domains that evolve over time and conditions – for example ^{137}Cs is both a radiological and chemical hazard, and organisms such as *Bacillus anthracis* cause both direct hazards from infection by the organism and also from the toxins generated by the organism over time. Such complexities are often discounted during evaluations of the potential risks and potential impacts posed by hazards. This also includes mixtures of hazard, degradation products or products of metabolic processes.

Here a conceptual framework for modelling complex simultaneous hazards dispositions, transport and evolution over time is presented. Hazard is conceptualised as a collection of continuously stirred tank reactors (CSTR) modelling the mass balance of hazard within discrete zones of arbitrary size. This is coupled to a mass transfer model that accounts for movement between zones. Evolution of hazard mass and type over time – including growth, interaction, degradation, reaction and transformation – is also conceptualised utilising a genericised Process Network Synthesis (PNS) approach. This framework is likely to have utility where complex interactions of hazard over time with objects within an environment is of interest, and where different scenarios and configurations require comparison. For example, determination of optimal policy to plan, prepare and respond to high risk emergency response situations involving hazard such as Chemical or Biological warfare scenarios is challenged by the inability to conduct real-world experiment. Modelling and simulation using the framework presented in this study could provide more detailed data on potential risks to populations and organisations in these settings. Concerns such as parametrisation and approaches to verification and validation of models constructed using this framework are also discussed.

Keywords: *Chemical hazards, biological hazards, radiological hazards, modelling and simulation, geospatial, integrated modelling*

Reducing Environmental Impact Statement processing effort and rejection risk by moving to data submissions

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Abstract: Environmental Impact Assessment (EIA) is the process for assessing the future consequences of a project or proposed action. Currently, Environmental Impact Statement (EIS) is the common practice to report the assessment, inform and drive decision-making processes regarding important environmental and socio-economic matters seeking sustainable development. The quality of EIS information is crucial for the assessment process, usually containing large amounts of complex data with a degree of uncertainty according to stage of the project lifecycle. Reducing this uncertainty regarding site-specific issues included in the EIA makes EIS creation both resource-intensive and time-consuming. Additionally, their production may require multiple parties' inputs, both for submission and assessment, which further raises costs and increases process complexity.

Reducing the required EIS creation resources (cost, time) and effort of managing the whole EIA process reduces the overall costs of, and risks to, developments. Due to resources and effort associated with data volumes, uncertainty and complexity, EIA may be withdrawn or rejected, or perhaps inadvertently accepted, regardless of their actual substance. Notwithstanding the process and administration, both EIS submitters and receivers will seek efficiency within the EIA process to address the objectives proposed by the assessment. Whatever reductions in effort can be made, the EIS contents (information, evaluation and management plan) are critical for an accurate environmental assessment; and they determine the submitter's capacity to address the environmental issues and concerns to ensure the EIS acceptance.

This paper proposes a way to substantially reduce the required resources and the overall process uncertainty of EIA addressing data structures and data management best practices taken from other data domains. Firstly, we review EIA/EIS data process *status quo* in two jurisdictions, Chile and Queensland, and compare them. Then, we consider emerging EIS handling best practice where, in Chile, we see Content Management Systems (CMS) being used to submit, manage and store submissions. Lastly, we step beyond EIA/EIS best/emerging practice proposing future practices using innovative data systems and integrating them with CMS processes which are the focus of our research.

Our research agenda looks to knowledge graphs for storing and exchanging EIS information since they are flexible data structures able to represent data across multiple domains. We propose moving EIS submitters and receivers away from document lodgement and processing, to standardised handling of knowledge graph data objects. In Queensland if this happens, not only will automation reduce effort and decrease rejection risk for submitters, but receivers may be able to automatically draw on data being created through current initiatives designed for other purposes that use knowledge graphs. Having two jurisdictions, Queensland & Chile, allows us to estimate breadth of the applicability of this approach.

Keywords: *Environmental Impact Statement, EIS, knowledge graph, CMS, data integration*

Comparing estimated years of life lost due to air pollution using system dynamics versus Leslie matrices

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Abstract: Ambient air pollution in the form of fine particulate matter < 2.5μm ($PM_{2.5}$) causes premature mortality. Reducing population exposure to anthropogenic $PM_{2.5}$ will increase life expectancy. We compare estimates of the impact of reducing air pollution to non-anthropogenic background levels on increased life expectancy using two alternative modelling frameworks: A) the commonly used ***Leslie matrices method*** and B) our proposed alternative: a ***system dynamics approach*** using aging chain stock-and-flow structures.

We simulated the reduction in future death rates in Sydney, Australia, for a scenario of reduction in $PM_{2.5}$ emissions and estimated the number of additional life-years lived. We estimated the baseline attributable risk using all-cause death rates linked with exposure estimates for $PM_{2.5}$ from a satellite-based GIS regression model. The anthropogenic component was estimated using a Chemical Transport Model. We then calculated the number of age-specific deaths attributable to anthropogenic air pollution. Years of life lost were estimated using both the Leslie matrices and the system dynamics methods and we evaluated these approaches in terms of their validity and flexibility to incorporate lag effects and the non-linear feedback between different sources of $PM_{2.5}$ pollution. Figure 1 shows the system dynamics model and highlights a feedback link between wood heaters and power stations, two important sources of $PM_{2.5}$ pollution in the study region.

Comparison of the Leslie matrices approach to the system dynamics approach suggests that the former is simpler, but the latter may provide greater flexibility to explore interactions (where decreases in emissions from wood heaters may result in increased emissions from power stations). In addition the system dynamics approach is also well suited to quantifying sensitivities based on many simulation runs, which is more cumbersome with Leslie matrices.

While our results imply that emission reductions for climate change mitigation may have co-benefits such as increased life expectancy, the existence of lagged effects and non-linear feedbacks between sources of pollution have the potential to complicate precise estimation. Methods such as those explored in this study will be useful in future assessments of both the costs and benefits of interventions to reduce human-made air pollution.

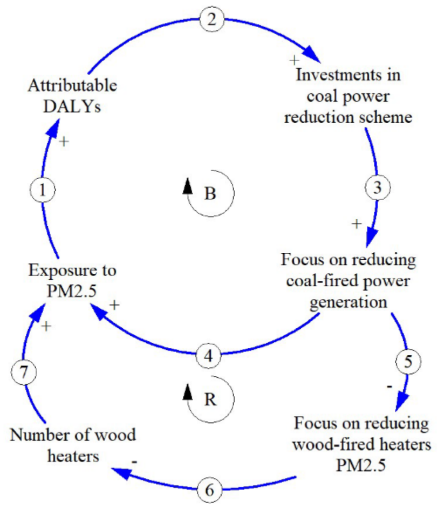

Figure 1. System dynamics model with feedback from wood heaters to power stations

Keywords: *Alternative modelling frameworks, complex systems, integrating environmental and health data, simulating future scenarios for interventions*

Identifying hotspots of infectious disease transmission using a random forest machine learning algorithm: a case study of lymphatic filariasis elimination in Samoa

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Abstract: Lymphatic filariasis (LF) is a mosquito-borne parasitic disease that can cause severe damage to the lymphatic system and long-term disability. The Global Programme to Eliminate LF has delivered medications to large populations in endemic areas (mass drug administration) with the aim of reducing infection to levels where disease transmission will be interrupted. A key challenge for achieving this is the detection of any residual foci and hotspots of transmission, meaning targeted surveillance strategies are needed as countries approach the end stages of elimination. This study aims to investigate geospatial modelling as a potential method for integrating health and environmental data to identify residual hotspots of LF transmission in Samoa.

To predict hotspots, we combined random forest (RF) models with generalized additive models (GAMs). Prevalence data for LF was obtained from field surveys in 2018 and 2019. Each survey sampled 35 primary sampling units (PSU, comprising of one or two villages) distributed over the three main islands (Upolu, Savai'i and Manono), with between 11 and 19 randomly selected households in each PSU. The 2019 survey sampled the same PSUs as 2018, but different randomly selected households. Using cross-sectional data of known infection locations from the 2018 field survey, a RF model was trained to predict probability of infection (antigen positive) in a household as a function of environmental data (temperature, rainfall, elevation, distance to water). Ten-fold cross validated predictions were then included as a covariate in a GAM, alongside a bivariate low-rank Gaussian process smooth on latitude and longitude. This allowed for any spatial variation in risk not explained by the environmental variables to be included in the model. The combined model was then used to predict the probability that infection prevalence in a household in 2019 was >10%. Households were considered as high risk if this predicted probability was >80%. The observed results of interest were whether a household had at least one antigen-positive resident (positive household), or more than one antigen-positive resident (multi-positive household).

The most influential predictor in the RF model was distance to water (gini impurity = 11.2). In the GAM, exclusion of longitude and latitude increased AIC from 492 to 498, indicating that proximity to an infected household was a predictor of infection risk in other households. The prevalence of infection amongst residents of low risk households was 3.6% (91 out of 2500) compared to 31.1% (32 out of 103) for high risk households. Households predicted as high risk by the model were significantly more likely to be positive or multi-positive ($p < 0.001$) (Fig 1). Our results indicate that geospatial modelling shows promise for stratifying infection risk at village and household levels, and demonstrates the value of integrating environmental data with health data for identifying residual hotspots, and thereby informing more targeted surveillance. Future work will explore the integration of additional environmental variables to further strengthen the spatial links between environmental health and infection risk.

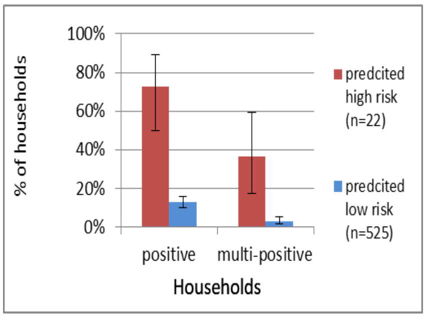

Figure 1. Comparison of positive and clustered households in high risk vs low risk household locations

Keywords: *Public health, geospatial modeling, lymphatic filariasis*

‘Detailed verification’: Extension to stochastic quantitative microbial risk assessment for water recycling

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Abstract: The benefits of a sustainable urban water cycle are growing in recognition. Access to alternative and diverse water supply sources is a key pillar underpinning the ‘water-sensitive city’, an ideal end-point for sustainable urban water management practice conceptualised in response to climate change. However, water recycling represents a unique public health risk profile that should be thoroughly assessed and appropriately controlled. Disease caused by pathogenic microorganisms is a primary concern.

There are only two widely-used methods to estimate treatment performance against pathogen reduction requirements. The first, and most comprehensive, is validation; the second is to sum indicative unit process performance levels derived from literature. However, these methods are impracticable for continued application throughout the service life of a water recycling scheme. The objective of this study was to establish an approach for the ongoing quantitative assessment of public health risk of operational water recycling schemes, providing sufficient assurance that public health objectives continue to be met. Such an approach is vital to account for changes to a scheme’s treatment processes or to the nature of the sewerage catchment over time, neither of which are captured by once-only validation campaigns or desktop analyses.

A novel method was established to do this, using indigenous surrogate organisms for the estimation of microbial $\log_{10}$-reduction values and associated public health risk. The levels of bacterial, protozoal, and viral risk for three water recycling schemes in the greater Sydney region, Australia, were analysed using quantitative microbial risk assessment (QMRA) and Monte Carlo simulation. Importantly, inter-unit process surrogate reduction results were used as a novel extension to the QMRA exposure assessment stage. Using this method, adherence to reference levels of risk for each of the three pathogen groups was successfully demonstrated. The extended exposure assessment provided new insight into the relative influence of unit processes on scheme risk, enabling targeted improvement of risk estimation.

Detailed verification fulfils a role distinct but complementary to that of common approaches to validation and verification. Importantly, it is suitable for ongoing assessment throughout the lifetime of a scheme, without interruption to supply and with low cost relative to validation. Consequently, detailed verification represents a useful and new component of public health risk assessment for water recycling schemes.

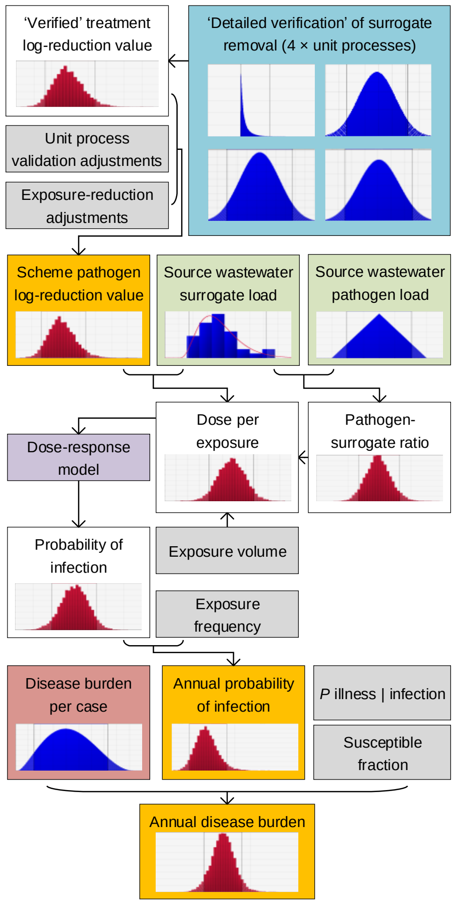

Figure 1. Conceptualisation of stochastic quantitative microbial risk assessment extended with detailed verification monitoring

Keywords: *Quantitative microbial risk assessment, stochastic modelling, water recycling*

Spatio-temporal modelling of human health impacts of air pollution exposure – what next?

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Abstract: The availability of (environmental) data has seen a surge in recent years, thanks to ubiquitous sensing, earth observation, and the emergence of small, portable sensors, at least in the Western developed world. In many low and middle income countries (LMCIs), however, data for instance on ambient air pollution are scarce, or even non-existent. At the same time, environmental change driven by population growth, urbanization, and global climate change, occurs at a speed and magnitude in those regions, which are unprecedented in recent history. With rapid technological development, a simple extrapolation of data availability and access in high spatio-temporal resolution everywhere, at any time, is an alluring assumption. Yet, without advanced data science methods and approaches for governance, resilience and transparency – from the collection and processing, to the storage and interpretation of data – vast new data streams will not automatically improve decision making.

Based on the discussion of key steps forward for the integration of environmental sensors and models in 2015[1], this extended abstract aims to provide an overview of the emerging challenges for the assessment of human health impacts of air pollution exposure. Showcasing recent research findings for public health effects of air pollution in the UK from local to national scale[2], respectively over a 40 year time period[3], the underlying sensor and data infrastructures required to conduct such assessment will be analysed. A review of the potential gaps and shortfalls in established scientific and regulatory monitoring and modelling activities with regard to how they affect decision making will then lay the groundwork for a discussion of potential future pathways for spatio-temporal modelling (and the required underlying data generation), with a focus on data-scarce regions with no or little existing environmental monitoring and data infrastructure.

The objective of this contribution is to set the scene for the session, and stimulate a wider discussion with the ultimate aim to convene a dialogue in the research community. As one key outcome of this dialogue, a scene-setting paper to map out the most promising pathways for environmental modelling, monitoring and data science will be developed, inviting contributions from the session and the wider MODSIM and iEMSs communities.

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Keywords: *Data science, environmental pollution, integrated modelling, public health*

BERTHA: The Danish Big Data Centre for Environment and Health

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Abstract: The BERTHA Big Data Centre for Environment and Health at Aarhus University, Denmark, aims to muster the huge potential opportunities from the Big Data revolution to help us understand the complex interactions between environmental pollutants and human health. Spatial lifecourse epidemiology and the exposome, are seminal concepts that underpin the centre, as we aim to recreate the lifecourses of the entire Danish population.

Key to this overarching aim is bringing together an interdisciplinary team of environmental and data scientists and clinicians to assemble, link and analyse diverse, rich (Big) datasets, develop algorithms and intelligent data analytics, all applied to our specific health outcomes that include cardiorespiratory and mental health. Novel data science methods are being adopted, including machine learning and deep data mining.

Significant computational challenges include Big Data collection and linkage from diverse data sources that vary over space and time. Data sources include national health registries, nationwide environmental exposures at fine spatial and temporal resolution, with an emphasis on air pollution; social media; personalised sensors; and individual biomarkers from blood bank, cardiac and physical activity cohorts. A further challenge involves developing Big Data analytics to extract pattern or trends from this complex set of data, a truly Big Data mining initiative.

The presentation will highlight the exciting possibilities and challenges of working with such rich data.

Keywords: *Big Data, Data Linkage, Data Analytics, Lifecourse, Exposome*

Air quality modelling of 2016 Madrid air pollution episode

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Abstract: Urban air quality is one of the major environmental issues for cities and traffic emissions are one of the major sources of air pollution in urban areas; in the case of Madrid, 90 % of emissions are produced by vehicles. Urban air quality presents a very important challenge due to spatial variability with high concentration gradients. In these cases, it is recommended to use computational fluid dynamics (CFD) models that explicitly resolve buildings and streets at high resolution. The aim of this work is to perform a simulation of a NO_2 episode during December, 2016 in Madrid (Spain) city. The episode occurred from December 26 to 30, 2016, where NO_2 hourly concentrations reached more than 250 µg/m^3 at several monitoring stations. In December 2016, the levels of NO_2 in Madrid were so high that authorities restricted access to the city centre for half of the cars based on whether the number plate was even or odd. The objective is to show how a multi-scale modeling tool from a mesoscale level to a micro-scale level can simulate the NO_2 peaks measured by stations.

A multi-scale modelling system using the WRF/Chem (NCAR, US) mesoscale model and applying a downscaling approach from regional to city-scale (1 km spatial resolution) as well as a CFD-RANS (MICROSYS) model (5 m spatial resolution) has been applied and evaluated. In case of the MICROSYS, has no chemical reactions implemented so to convert NO into NO_2 concentrations, a basic chemical scheme was developed in the CFD model. Traffic emissions are produced with the same horizontal resolution using the emission factors from EMEP-CORINAIR Tier 3 methodology (UNECE Air Convention). Traffic activity is one of the main input data for estimating road traffic emissions. The number of vehicle entries, vehicle mileage and speeds are needed for a detailed emission map. The traffic flows and vehicle speeds were simulated with the microscale SUMO model (DLR, Germany) using real traffic counters to calibrate the traffic demand. The simulations cover a period of 2 (spin up) + 7 days. The CFD simulation reproduces the interactions between air flow and buildings with a very detail emission sources (traffic).

We show a substantial improvement in the model results when comparing with the CFD model results with the mesoscale model results. The results show also a much better simulations of the daily NO_2 peaks. The CFD 5m simulation take into account the buildings and the complexity of urban environment to capture the complexity of local effects and reproduce the important local effects. The CFD model used has certain limitations such as using it in stationary mode and using a RANS approximation; the stationary state only provides an instantaneous distribution of pollutants. Of course with a higher computational capacity these limitations could be solved for example by using an LES (Large Eddy Simulation) approach. The coupled WRF/Chem-CFD modelling system is a reliable method to understand the complicated flow and pollutants dispersion within urban areas. The modelling system can be used as a tool to evaluate different emission reduction strategies at street level.

The integrated modelling system is suitable for testing and evaluating traffic-related emission mitigation strategies on a scale of metres and obtaining information on their effectiveness without actually having to implement it. One of the uses of the proposed modelling system is the possibility of carrying out various simulations changing traffic conditions and even changing the urban morphology (for example putting natural or artificial barriers for pollution) to obtain the impacts on the concentrations of this type of measures.

Keywords: *Air quality, simulation, mesoscale, microscale, traffic emissions*

Where do we recreate? Comparison of different methods to determine importance of site characteristics for outdoor recreation

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Abstract: Residents of industrialized countries place increasingly more value on leisure time. For many alpine and remote municipalities, revenues from tourism and recreation belong to the most important sources of income. At the same time, these activities generate large carbon footprints through traffic. Identifying the drivers of demand for outdoor recreation is essential for a sustainable future transport and landscape planning. By using different types of regression models, we compared four different methods to determine the importance of variables quantifying landscape characteristics for explaining outdoor recreation day trips.

The regression models were:

- Generalized Linear Model of the Poisson family
- Random Forest regression
- Gradient Boosting regression

The applied variable importance measures were:

- Perturbation variable importance
- Hierarchical Partitioning
- Gini Index
- Gradient Boosting node impurity

The overall pattern of variable importance complies between the different regression models, but there are also some obvious differences. Two variables, namely population density and the number of land use counts dominate variable importance for all methods and are the by far most important predictors. Variables of medium importance can hardly be identified. There are only fractional differences between the importance indices of the low importance variables. Therefore, the overall ranking of low importance variables differs substantially between different models.

Keywords: *Random Forest, Gradient Boosting, Generalized Linear Models, variable importance*

Estimating the impact of mass-drug administration to eliminate lymphatic filariasis in American Samoa

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Abstract: Lymphatic filariasis (LF) is a mosquito-borne parasitic infection common in many tropical regions. Though asymptomatic for many, globally 36 million people live with disfigurement and disability due to severe swelling of the limbs or scrotum caused by high-intensity infections. Between 2000 and 2006 American Samoa (AS) underwent seven rounds of mass drug administration (MDA) as part of the Global Programme to Eliminate Lymphatic Filariasis. Despite significant reductions in prevalence, there is evidence of resurgence prompting further rounds of MDA. The aim of this study was to compare the efficacy of different MDA strategies for the elimination of lymphatic filariasis in American Samoa and understand the long-term risk of resurgence.

We used GEOFIL, a spatially-explicit agent-based modelling framework to predict the prevalence of microfilaraemia in the AS population. The model includes individual-level information on disease status, age and gender, with short-range transmission (<100m – the flight range of the Aedes polynesiensis vector) centred at schools, workplaces and households, and long-range transmission (length of the country) enabled by daily commuting between these locations. We ran ≥50 simulations each for different combinations of MDA parameters including coverage (50-90%), drug combinations (diethylcarbamazine citrate + albendazole [DA] vs. ivermectin + DA), number of treatment rounds (2-5), and time between rounds (1-2 years). All simulations covered the years 2010 to 2035, with the first round of MDA in 2018.

Though all three drug MDA strategies with coverage ≥80% were able to reduce the prevalence of microfilaremia down to 2010 levels, prevalence increased once more after the end of MDA in nearly all scenarios and simulations. Only four or five rounds of three drug MDA with 90% coverage were able to reduce prevalence to zero and then only for <5% and <45% of simulations respectively. Where these strategies failed to reduce prevalence to zero, prevalence was very low (mean 0.05% and 0.02%) but on the rise by 2030. The prevalence of microfilaremia was consistently lower in six- and seven-year-olds than the general population, often reaching zero by 2030 in the most successful strategies despite ongoing transmission in other age groups. Strategies with one- or two-year intervals between rounds led to similar reductions by the end of MDA, though both reduction and resurgence were delayed by the use of longer intervals.

In American Samoa, resurgence is likely in the long-term even after MDA strategies with four or five rounds, three drugs, and high coverage. Therefore, ongoing surveillance and improved strategies for identifying residual foci of transmission are key to achieving elimination. The recommended surveillance of six- and seven-year-olds may delay the detection of resurgence. Surveillance of older age groups should be considered.

Keywords: *Lymphatic filariasis, mass drug administration, elimination, agent-based model*

Next-generation modelling of pathways to sustainable land-use and food systems for Australia

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Abstract: Land is a limited resource subject to increasing demand from multiple uses and is faced with myriad challenges to meeting these demands. Australia's agricultural land is said to feed 60 million people worldwide and global demand for crops and livestock is set to increase by 50% or more by 2050. Agricultural land-use is both a major source of greenhouse gas emissions at the same time as being at the forefront of the battle against climate change via its ability to store carbon in soils and biomass. In parallel, the degradation of natural capital and the loss of productive capacity is also mounting via processes such as climate change, soil erosion, dryland salinization, and biodiversity loss. How Australia can meet increasing demands on land while facing multiple pressures and achieve the UN Sustainable Development Goals (SDGs) is a key question for agricultural and environmental policy, planning, and management.

The urgent need to quantify the sustainability of global food and land systems has led to an upsurge in the development of land-use dynamics models and scenario analyses in recent years. The Land-Use Trade-Offs (LUTO) model is a high-resolution integrated environmental-economic of future spatiotemporal dynamics of land-use and its impacts of a range of policy options under alternative future scenarios to 2050 in Australia's intensive agricultural land. A 2017 study using LUTO published in *Nature* found few future pathways that could see Australia achieve multiple SDGs in land systems.

Land-Use Futures is a major new 3-year collaboration between ClimateWorks, Deakin University, CSIRO and other agencies which aims to renew the search for pathways to sustainability for Australia's land systems. The Land Use Futures project combines one of the most ambitious and extensive participatory approaches ever attempted in land-use modelling, with a substantive new modelling effort to extend the scope and application of the LUTO model for the quantitative assessment of Australian land-use in face of future uncertainties. A total of six workshops have been run in capital cities around Australia, with around 150 participants representing more than 100 organisations, including multiple sectors of government, industry, and civil society. Culminating in the national *Natural Capital Summit* in Brisbane in June 2019, the workshops were designed to elicit input from participants on key uncertainties, indicators, and interventions to support modelling of sustainable pathways for Australia's land-use and agri-food system.

The LUTO model will be extended in several ways including expanding to include northern Australian rangelands and dynamics in other land-uses such as forest cover and urban development. New uncertainty dimensions (e.g. change in global diets, social license to operate) will be considered in the development of scenarios and pathways by using state-of-the-art computational tools and techniques. Quantitative indicators of sustainability (e.g. soil carbon, land degradation, agri-chemical pollution) will be added to enable more comprehensive tracking of progress towards the SDGs. New land-use options and policy/management interventions will also be added which will involve extensive new modelling of the environmental and economic performance of interventions over space and time under uncertainty.

A new generation of *exploratory modelling* approaches will inform a new search for insights into the robust selection of sustainable pathways for land-use futures for Australia from the *big data* created by multi-dimensional evidence-based projections under uncertainty. A large ensemble of future projections will be created combining different interventions under different scenario settings for multiple dimensions of uncertainty. A mix of different search strategies in exploratory modelling, including stress-testing, sensitivity analysis, scenario discovery, option space analysis, and robust multi-objective optimisation will be used to inform the design of sustainable pathways. Insights on modelling sustainable pathways for Australia's land-use and food system will be joined-up with other national efforts under the global Food, Agriculture, Biodiversity, Land, and Energy initiative (FABLE) and the Food and Land-use Coalition (FOLU) to ensure a coherent global approach.

Keywords: *Land-use, scenario analysis, agriculture, food-system, sustainability*

MODIS vegetation cover data to monitor sustainable land management

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Abstract: Monitoring vegetation cover is a useful practice in assessing levels and trends in sustainable land management across landscapes. This project explored the application of fractional vegetation cover data as a tool for ongoing monitoring of vegetation cover and sustainable land management across New South Wales (NSW). The data was derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) dataset (version 310) as described in Guerschman *et al*. (2018), available from the CSIRO MODIS product website and viewable through the GEOGLAM RAPP website. Vegetation cover includes photosynthetic vegetation (PV) that comprises living vegetation and non-photosynthetic vegetation (NPV) that comprises dead vegetation but still serves to protect the soil surface.

The approach adopted builds on the concept of land management within capability (LMwC) (Gray *et al.* 2014) using vegetation cover levels as an indicator of land management. This concept recognizes the principle that degradation occurs when land is not used or managed within its inherent physical capability. The scheme examines the proportion of time a given area of land, or a specific pixel, remains above a target vegetation cover level, eg, 50% or 70%. The target vegetation cover level is an estimate primarily based on the slope and the annual rainfall of the site, being guided by available literature on sustainable vegetation cover under different conditions (eg, Lang and McDonald 2005, OEH 2012). It principally considers the land capability issues of water and wind erosion. Target vegetation cover levels decrease under gentler slope gradients and drier conditions as shown in Table 1. Other approaches to deriving target vegetation cover are being explored, including the use of cover levels required to maintain tolerable erosion and soil loss.

Table 1. Target vegetation cover in different rainfall and slope regimes (%) *(preliminary estimates)*

Slope (%)/ Rainfall (mm pa)	1: <1	2: 1-3	3: 3-10	4: 10-20	5: 20-33	6: 33-50	7: >50
1: Extreme dry (<200)	25	25	25	25	30	35	40
2: Very dry (200-300)	30	30	30	35	40	45	50
3: Dry (300-500)	40	45	50	55	60	65	70
4: Mod moist (500-700)	40	45	50	60	70	80	90
5: Moist (700-900)	40	50	60	70	80	90	100
6: Wet (900-1200)	40	60	70	80	90	100	100
7: Very wet (>1200)	50	70	80	90	100	100	100

The analysis involved comparing the target vegetation cover levels for each pixel with the proportion of time the vegetation cover has been above that target level over a given time interval. The higher the proportion of time the site exceeds the target vegetation cover level, the more sustainable is the land management (Table 2).

Table 2. Sustainability of land management based on proportion of time above vegetation cover target

Proportion of time above target	Sustainability of land management
>95%, 12 months pa	1. Very high
80-95%, 10-11 months pa	2. High
70-80%, 9 months pa	3. Moderate
50-70%, 6-8 months pa	4. Low
<50%, 1-5 months pa	5. Very low

Results can be derived over specific periods of time of interest (for example 2017-18) or averaged over the entire 2001-2019 period for which MODIS data is available. They have been prepared over the entire state of NSW, all individual NRM regions and specific localised areas of interest. Results are useful in identifying regions and specific locations where more sustainable land management practices should be encouraged.

Keywords: *MODIS vegetation cover, land capability, sustainable land management*

A meta-model for comprehensive environmental risk assessment of global food system futures

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Abstract: The global food system is a key driver of global environmental impact, and has been directly linked to the transgression of specific ecological thresholds or planetary boundaries, especially those of land-system change, climate change, biosphere integrity, biogeochemical flows and freshwater use. A growing number of modelling studies employing a diverse array of forecasting methods and scenario specifications have estimated environmental implications of alternative food futures for a range of business-as-usual (BAU) and alternative intervention scenarios. These projections have not been previously synthesized and systematically compared against *food system specific planetary boundaries* (hereafter simply *environmental limits*) while comprehensively accounting for study bias and the considerable uncertainty range in indicator choice and proposed ecological thresholds. This talk will present novel findings from statistical meta-model for calculating the environmental risk associated with global food system futures, developed through a meta-analysis of 910 published food scenarios across 60 studies for the year 2050.

We first carried out a literature review to define ranges for environmental limits for the year 2050 as a series of triangular probability density functions for a number of environmental indicators (hereafter *control variables*) relevant to four planetary boundaries: Land-System Change (3), Freshwater Use (1), Climate Change (4), Biogeochemical Flows (4). The control variable distributions formed the basis for the analysis by providing a measure of absolute sustainability encompassing current uncertainty in ecological limits. Using the control variable estimates for each of the reviewed scenarios as dependent variables, we fitted 12 linear mixed models and used these models to generate a comprehensive database of 78,400 projections for 2050 encompassing all possible combinations of food system interventions. Interventions were represented as independent variables (i.e., crop productivity, livestock productivity, water-use efficiency, nutrient-use efficiency, population, animal and vegetal caloric intake etc.) with a number of levels representative of different degrees of mitigation effort. Projections used as inputs to the cumulative distribution functions of the 12 control variables in order to calculate overall exceedance risk and effect size (risk difference) associated with different intervention levels. Last, we created four meta-analytic global food system intervention scenarios (High Challenges, BAU, Ambitious Action, Transformative Change), ranging from highly pessimistic to highly optimistic, and used the projection database to evaluate and compare exceedance risk across control variables.

Our findings support recent literature by highlighting the extremely high risk of planetary boundary exceedance under BAU and other realistic intervention scenarios, with only highly ambitious mixed interventions incorporating diet and efficiency measures capable of significantly reducing the probability of exceedance of key environmental limits. Our risk assessment meta-model and the accompanying scenario projection database provide a comprehensive resource for considering the relative effectiveness of available interventions across different control variable and planetary boundaries. Our synthesis makes a significant and well-timed contribution to the literature on future food systems by emphasising the unacceptably high risk of planetary boundary exceedance under ambitious but realistic mitigation scenarios, and the need for concerted global efforts to adapt to the inevitable transgression of the Earth's safe operating space.

Keywords: *Food systems, mixed model, scenario, sustainable agriculture, planetary boundaries*

Land use change and its impact on soil erosion in Central Highlands of Sri Lanka using GIS

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Abstract: Rapid changes in land use and land cover (LULC) due to urbanization and expanding agricultural areas create immense pressures on sustainable land-use systems. Degradation of land resources induces soil erosion rates while reducing the diversity of plants and crops which leads to forming marginal lands. Hence, scholars are more concern about understating land use dynamic and its impact on sustainable land-use systems. This study was carried out in Sri Lanka: a tropical country and island nation. Central Highlands of Sri Lanka is dominated by rain-fed farming systems, and it is subjected to the disruption of agro-ecosystems, high degree in erosion of soil and biodiversity and degradation of community bio-cultural food systems due to climate variation mainly precipitation changes and other environmental and social pressures. Hence, timely and accurately vulnerability assessment and addressing these issues help to improve agricultural food security in the country. This paper attempts to identify the land-use change and its impact on soil erosion and potential vulnerability for landslides in a Geographical Information System (GIS) environment. Revised Universal Soil Loss Equation (RUSLE) model and frequency ratio method were employed.

Required geospatial data were obtained from multisource such as Landsat 7, 8 imageries in the year 2000 and 2019, LULC maps, soil data, topographic maps, precipitation data, land management practices and landslide incidents data for the study period. Vulnerability to soil erosion was identified by integrated modelling approach and classified into five classes: very low, low, moderate, high and very high. Land use dynamics were identified by image analysis tools in GIS environment. Seven land use classes were identified and classified as Dense forest, Water bodies, Stream, Paddy lands, Urban area, Cropping area and Low dense forest. Interactive supervised classification method was used to derive the LULC classes and spatial analysis tools were employed to find changes in LULC classes. Landslide incidents data were used to generate landslide incidents map and it was overlaid on to generated soil erosion hazard map to identify the relationship between hazard classes and landslide frequency ratio.

The study shows that the average rate of soil erosion in the study area is about 56 t $ha^{-1}yr^{-1}$. The generated soil erosion hazard map clearly indicates the area under very high class was 11% ($533km^2$) from the total land area. The analysing of the LULC classes reveals the Cropping and the Urban areas have been increased by 18% and 3% in the study area respectively during the study period. The prominent land-use change can be observed as "Cropping area" between the year 2000 and 2019. The landslide incidents frequency ratio of the study area has used with soil erosion hazard classes and land use classes to find highly vulnerable areas for soil conservation. There is a significant relationship with soil erosion hazard classes and landslide incident frequency ratio. This can be concluded as the intensification of land-use change has been a severe threat for sustainable land-use systems and the impact on increasing soil erosion hazard in the study area. This paper extended the body of knowledge in new methodology on prioritizing areas for soil conservation using landslide frequency ratio, soil erosion rate and land use change using remote sensing data : Landsat imageries in GIS environment particularly in Central Highlands of Sri Lanka.

Keywords: *Land use land cover (LULC), Frequency ratio, Landslides, RUSLE, Sri Lanka*

Consumers' risk perceptions and risk reduction strategies for organic products

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Abstract: Over the past three decades the demand for organic products has risen steadily, as has their price. Organic products are highly sought after as they are produced without using conventional pesticides, chemical fertilisers, bioengineering or ionising radiation. Despite the common belief that organic products are better for our health than conventional products, most consumers, especially those in developing countries, cannot define what an organic product is, nor identify what characterises them.

Scepticism about the virtues of organic products, especially as they are sold at premium prices, increases consumers' perceptions of risk, which in turn, affects their attitudes and, consequently, their purchasing decisions. Consumers' perceptions of risk and their risk reduction strategies are considered crucial in conventional product marketing. These factors are known to influence consumer behaviour and impact upon consumers' willingness to pay. Surprisingly, there has been to date, no integrated study of consumers' perceptions of risk and their risk reduction strategies, including their willingness to pay for organic products.

This study applies structural equation modelling to empirically examine consumers' willingness to pay for organic products. This study uses a sample of 784 Thai respondents who are the purchasers of organic products. Thailand was chosen for this case study because the organic products markets and emphasis on organic farming are in the initial stage of development, which is similar to other developing countries. The study found that consumers' risk perceptions have a positive influence on their willingness to pay for organic products, while consumers' risk reductions strategies have a negative influence. In terms of consumer risk perceptions, key factors were psychological, social and time risks. Consumer risk reduction strategies included focusing on organic product handling processes, searching for more information about organic products, selecting products that are certified and choosing well-known brands. These findings add to the literature on organic food marketing and can be used in both developed and developing countries by policymakers, marketers and farmers to encourage greater consumption and confidence in organic produce.

Keywords: *Structural equation modelling, organic products, willingness to pay, risk perception, risk reduction*

Providing evidence-based support for poverty alleviation and sustainable development in tropical regions

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Abstract: Madagascar faces many environmental challenges, with deforestation, soil erosion, and other forms of land degradation frequently highlighted. To devise solutions to these problems and accommodate sustainable development, there is a need for considering degradation and development processes in an integrated way in order to create synergies and avoid short-term biases with significant long-term trade-offs. Such an integrated, forward-looking scenario approach requires understanding the drivers and effects of environmental, economic and social systems.

The World Bank has initiated the LAUREL program to support integrated decision making for landscape management across sectors and levels of government by promoting improved tools for land use planning and management. These result in more evidence-based decision making around long-term sustainable land use, which in turn aims to improve resilience and the ability of landscapes to deliver ecosystem services and development benefits.

We present a generic integrated land use modelling platform (LANDSIM-P) with an application to Madagascar, which has been developed as part of the LAUREL program through a co-creation approach involving potential users across various governmental agencies, researchers and IT-specialists. The developed platform includes a suite of tightly-coupled models representing land use, farmer decisions, hydrology, vegetation, crop yields and soil processes. Processes are modelled with a high level of spatial detail to capture the local context, both in terms of the environmental conditions as well as the household types that manage the land, as the decisions households can make depend on the socio-ecological system they operate in. To understand the emergent behaviour across sub-systems, these components represent feedbacks between the various socio-economic and bio-physical processes. Model components operate with a temporal resolution of months to years simulating developments several decades into the future. This dynamic nature of the system provides an improved understanding of future developments and allows users to explore the impact of various uncertainties. Furthermore, the model can be used to assess the issues and benefits of planning and management alternatives and as such, provides decision-makers with an evidence-base for including medium to long term consequences in the planning and policy practice. For example, the dynamic and integrated nature of the system allows simulation of soil degradation due to poor management practices, the resulting negative impact on yields, ultimately increasing the pressure to clear new forests. Conversely, the system shows how improved practices can lead to improved yields, providing a stepping-stone to self-sufficiency and production of cash crops to improve livelihoods.

Acknowledging that merely developing a modelling framework is no guarantee for its actual use in practice, usefulness and usability have guided development of LANDSIM-P throughout the project. Through a series of workshops, input was provided to both the development of the generic system as well as a specific use case for Madagascar. The latter encompassed the development of policy-relevant scenarios focusing on key issues on the island, key drivers impacting on those, and possible planning and management alternatives to steer developments in the desired direction. Simulated scenarios were subsequently discussed with the user group to assess their relevance in practice and to obtain feedback for the further development of the platform. Although the platform is developed based on national data for Madagascar, the principles are globally applicable in tropical regions.

Keywords: *Integrated land use modelling, policy support, land degradation, poverty alleviation, farm systems*

Hybrid analytics – harnessing the best of process-based modelling and machine and deep learning

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Abstract: Data is growing at an exponential pace, and this growth undoubtedly provides opportunities for significant scientific and technological advancements. Due to this data growth, machine and deep learning (ML-DL) approaches are becoming increasingly popular in prediction and are now quite common. But, if there is insufficient data, the data contains biases, or the solution is well beyond the range of conditions from which the data was collected, then the computer cannot learn and accurately predict the future. In these instances, mechanistic or process-based models, which seek and represent causality rather than correlation, are useful - even essential - for prediction despite at times being more computationally demanding.

Historically, process-based and ML-DL modelling are often considered at different ends of a paradigm. Yet when combined *via* hybrid analytics they are complimentary by combining the power of data (ML-DL) and physical understanding (process-based). Hybrid analytics approaches enable use of real-time data combined with understanding of physical and biological processes, learn from past results, enable dynamic recalibration for improved forecasting. The combination allows us to overcome lack of scalability of process-based modelling and the generality of machine learning. Grassland based primary production systems lend themselves to hybrid analytics approaches, as we are often data-poor for ML-DL in certain areas (e.g. pasture production, nitrogen leaching) but in other areas know the casual biophysical relationships (e.g. between weather, soil structure, soil fertility and pasture production) well. Alternatively, we have a wealth of data for ML-DL but don't know biophysical relationships, e.g. management responses to environmental perturbations.

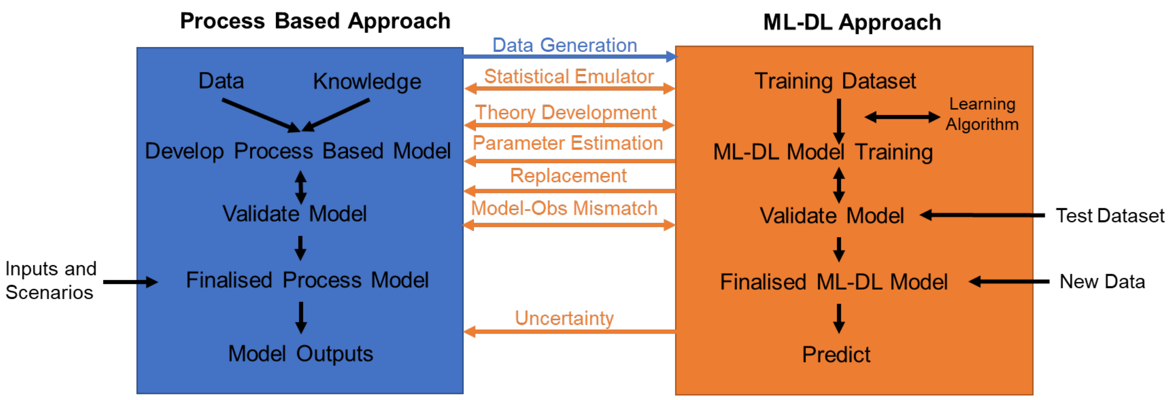

Figure 1. Comparison and synergies between process-based and ML-DL approaches

Examples of hybrid approaches (Fig. 1) include: data generation by a process-based model for ML training; statistical emulators; theory development and pattern extraction; parameter estimation or data imputation *via* machine learning; replacement where a process-based component is replaced with a ML-DL model; model-observation mismatch identification; and uncertainty representation including Bayesian techniques.

We will present the range of hybrid analytics approaches and opportunities including their strengths and challenges. We will cover key principles of hybrid analytics including the need to: still comply with physical laws; feature an interpretable structure; be fully data-adaptive where theory is weak; be validated and regularly reviewed; not unduly compromise accuracy in pursuit of speed; and avoid extrapolation beyond the domains. Hybrid analytic approaches hold great promise to enhance prediction, reduce bias, and improve understanding of uncertainty but, as with all data sciences, the approach chosen should be fit for purpose.

Keywords: *Process based modelling, machine learning, deep learning, prediction, simulation*

Modelling wildlife species abundance using automated detections from drone surveillance

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Abstract: Reliable estimates of abundance are critical to the conservation of threatened species. Aerial surveying is a sampling method that has been used to estimate wildlife abundance over large or inaccessible areas. An increasing trend in aerial surveying methodology is to use remotely piloted aircraft systems (RPAS), also known as drones, in lieu of traditional manned aircraft systems such as planes and helicopters. Studies which used RPAS instead of manned aircraft have recently attempted to analyse imagery using automated detection methods. While there are a number of advantages to this approach, there are also potential issues in abundance estimation using this data since the errors associated with using these approaches are largely unaccounted for in established models of abundance estimation.

In this paper we applied a model developed by Terletzky and Koons (2016) for fixed wing survey, to data derived from RPAS surveys that has been processed by an automated detection method for koalas. The data collected enabled ground-truthing of detections which allowed both the probability of detection and the probability of duplicate detection to be accounted for in abundance estimates, as well as a comparison between the estimates and the true number of koalas present on site.

Overall, it was found that the Terletzky & Koons (2016) method resulted in artificial inflation of abundance estimates when using data collected from RPAS surveys with automated detection. This is likely to have resulted from false positive detections, which can have a considerable impact on the accuracy of automated wildlife counts. Incorporating more sources of error than the probability of detection and duplicate detection appears to be essential to improving abundance estimation for these novel survey methods. An exploration of additional covariates that could affect detection in RPAS-derived thermal imaging due the unique constraints of these technologies should be considered in future model development.

Keywords: *Abundance modelling, wildlife detection, unmanned aerial vehicles (UAVs), machine learning*

EXTENDED ABSTRACT ONLY

On-vessel video analysis for fish species identification using deep learning

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Abstract: The sustainable management of fisheries is reliant on data that accurately reflect the activities of fishing vessels, increasing transparency within the commercial fishing industry and ensuring fishing operations remain sustainable into the future. The use of on-vessel human observers to enforce fisheries management policy is an expensive and potentially dangerous practice. The transition from on-vessel observers to camera systems, whilst reducing risks to observers, creates a significant volume of data that is required to be processed by trained analysts and as such it is not only time consuming but prohibitively expensive to analyse all footage obtained across a monitored fishery. To address this, CSIRO's Marine Visual Technologies (MVT) have developed *Wanda*, a video processing system utilising a convolutional neural network (CNN) based back-end capable of automating fish detection and species identification. *Wanda* is capable of processing 100% of footage obtained during a fishing trip, detecting and classifying fish based on species. A Graphical User Interface presents a summary of the vessel's catch to a human operator, allowing the system's findings to be audited and any errors in species identification corrected.

Figure 1. The graphical user interface of the *Wanda* software following the processing of a fishing event on a commercial vessel.

The dynamic nature of a long-line fishing vessel's deck often requires multiple fish to be identified, classified and tracked simultaneously from footage captured on low-resolution cameras, often with uncontrolled background and illumination in rough seas. To address these challenging conditions, TensorBox, a robust framework for object detection within images was utilised alongside an initial, manually labelled 'training' set of 1700 frames from vessels operating in Australia's Eastern Tuna and Billfish Fishery. Early versions of *Wanda* incorporating an object detection framework backboned with ResNet using transfer learning techniques can achieve an accuracy of 98.58% for targeted objects (both humans and fish).

Two detectors were trained separately for fish and humans to reduce the variation between the two object classes. For the human detector, our model can achieve an accuracy of 99.38%, and with the fish detector, we obtained an accuracy of 95.4%.

To further increase the accuracy of species identification moving into the future, we seek to abstract metadata from the integrated video-recording system, integrating it with pre-existing species distribution models using Multiview Leaning.

Keywords: *Machine learning, neural network, fisheries sustainability*

Ancient barrier lakes developed in the Golmud River valley, NE Qinghai-Tibetan Plateau: Implications for the future hazard prevention for downstream city and salt factories

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Abstract: The nature hazards associated with extreme climate events are constantly concerned by geologists, especially the barrier lakes triggered by strong precipitation in the background of global warming at the arid/semiarid areas. In this study, a series of ancient barrier-lake sediments were found in the Golmud River drainage basin of the eastern Kunlun Mountain on northeastern Qinghai-Tibetan Plateau. In general, these lacustrine sediments mainly consist of the laminated silty clay, silt and sand layers, and the elutriated gravel layers by lake water deposited where the shoreline was located after formation of the barrier lakes (Figure 1). Our preliminary Optically Stimulated Luminescence (OSL) dating results show that the barrier lakes were formed at 43.4±2.6 ka, 26.2±2.1 ka, and 9.7±0.5 ka, these ages are corresponding to the wet climate periods of the past 50 ka. In addition, the north-south huge alluvial fans originate from the tributary valleys also show common similar OSL ages with these barrier lake sediments, so we infer that the fast deposited alluvial sediments induced by floods in the wet palaeoclimate periods, which could be finally dammed the river and resulted in the development of the barrier lakes. It follows that the formation of ancient barrier lakes is closely related to abrupt floods under the humid palaeoclimate condition in the Golmud River catchment. Therefore, this geologic hazard should be given rise to a caution for the flood control safety and risk assessment of the downstream Golmud City and Qarhan Salt Lake industry, especially in extreme climate event conditions in future.

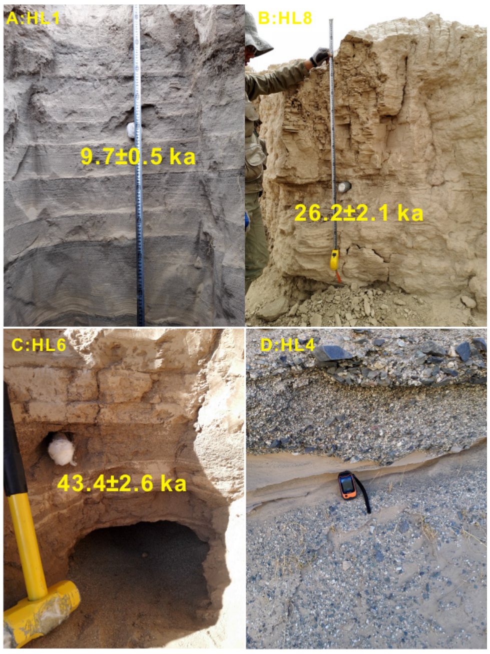

Figure 1. The sections of ancient barrier lakes show the horizontal lacustrine sediments, elutriated gravels and the OSL ages

Keywords: *Ancient barrier lakes, OSL ages, Golmud River, Geologic hazard*

Factors contribution to oxygen concentration in Qinghai-Tibetan Plateau: A preliminary study

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Abstract: Oxygen (O_2) is essential for physiological activity in humans. On the Qinghai-Tibetan Plateau, with an average altitude of more than 4 km, hypoxia can seriously damage local residents' health, especially the respiratory system. When an organism cannot fully compensate for insufficient physiological function caused by hypoxia, acute and chronic mountain sickness (AMS and CMS) will occur. Previous studies have suggested that the relative oxygen concentration (ROC) in the near-ground air shows no obvious changes at different altitudes. However, during field work in the Qinghai-Tibetan Plateau, we found that, in addition to altitude, surface vegetation coverage and weather conditions may also have an impact on ROC. The results of data analysis showed that altitude and 500 hPa air temperature (500 hPa-T) were negatively correlated with ROC, while vegetation coverage was directly proportional to ROC. Based on principal component analysis (PCA), the results indicated that altitude, vegetation coverage and 500 hPa-T accounted for 65.5% of the total variance in ROC, of which the variance interpretation rate of vegetation coverage was highest (33.1%), followed by 500 hPa-T (28.5%) and altitude (3.9%). Absolute oxygen concentration (AOC) was calculated using the Ideal-Gas Equation. Using this equation, we found that altitude, vegetation coverage and 500 hPa-T accounted for 78.9% of the total variance in AOC, of which the variance interpretation rate of altitude was highest (45.9%), followed by vegetation coverage (18.5%) and 500 hPa-T (14.5%). AOC was negatively correlated with the incidence of CMS, and elevated AOC significantly reduced the incidence of CMS. The science community should pay more attention to this topic as a further decrease in ROC could significantly increase instability and risk in populations at high altitudes. These findings could enhance our understanding of the relationships between oxygen concentration, altitude, vegetation, weather conditions and their interactions. In addition, this research may not only play an important guiding role in human and animal health in high altitude areas, but also significantly deepen our understanding of the risks in high altitude environments under global warming both theoretically and practically. Multi-source data, including *in-situ* measurement data, remote sensing data, and model reanalysis data, will facilitate further implementations in this direction. Future work can be carried out using more fixed-point observations and by expanding the spatio-temporal extent of relevant data in high altitudes.

Keywords: *Oxygen concentration, Qinghai-Tibetan Plateau, life and health, altitude, vegetation, meteorological factors, principal component analysis (PCA)*

Trends and risk evolution of drought disasters in the Tibet Region, China

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Abstract: The risk posed by natural disasters can be largely reflected by hazard and vulnerability. The analysis of long-term hazard series can reveal the mechanisms by which risk changes. Drought disasters are one of the main types of disaster in the Tibet Region (TR) of China. In this study, using statistical drought disasters data in the TR from 1912 to 2012 and socio-economic statistics for five periods between 1965 and 2015, and adopting standard statistical analyses, a wavelet analysis, and a risk assessment model, we first construct the index system for drought disaster risk assessment, and then assess the risk of drought disasters and analyze the mechanisms of changes in the risk. The results showed that the occurrence of drought in the TR had three distinct cycles during this study periods, with durations of 5, 15, and 27 years respectively. The frequency of drought in the TR showed increasing trends, and the cycle of drought had been prolonged. From 1965 to 2015, the risk of drought disaster in the TR is significantly increased with the growth rate of 6.8% in high-risk area. In addition, the severity of drought had enhanced, especially in Qamdo. The increased vulnerability locally and significantly enhanced hazard of drought disaster, with a shrinkage of 16.3% in the low-value area and an expansion of 7.4% in the high-value area, being the determinants of drought disaster risk. Therefore, agricultural areas in the TR are the focal locations where risk of drought disaster needs to be managed.

Keywords: *Tibet, TAR, Tibetan Plateau, drought disaster, risk evolution*

Heat wave with high impact on human health under global warming

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Abstract: Heat wave (HW) is one of extreme meteorological disasters in summer, which brings sever impact on human health and labour loss. Because climate change has become the biggest global health threat of the 21st century, future projection of global HW is unprecedented necessary for disaster prevention and mitigation. Therefore, this study projected HW events with high impact on human health by using excess heat factor as the HW definition based on ScenarioMIP experiments from the Coupled Model Intercomparison Project Phase 6 (CMIP6). In observation, the accumulated days of summer HW events with high impact on human health mainly occur in extratropical regions. The maximum HW days appear along 30°S and 30°N, respectively. We further evaluated the simulation of HW with high impact on human health by CMIP6 models and found the spatial and temporal distribution of HW days could be roughly reproduced. Therefore, these models were used to project this type of HW in the future. Then we purposely defined the ratios of accumulated days of HW averaged over tropical regions against extratropical regions in Northern/ Southern Hemisphere to describe the relationship between HW days in tropical and extropical regions. The results show that these ratios turn from less than 1 in present to greater than 1 in late 21st century, which indicates that the HW in tropical regions will remarkably increase in the future. Further analysis shows that this significant change of HW days with high impact on human health should be ascribed to the change of temperature variability. Recognizing the characteristics and understanding the mechanism of HW with high-impact on human health under global warming is crucial in the mitigation of risks and in adaptations to climate change.

Keywords: *Heat wave, human health, future projection, CMIP6*

Footprints of Atlantic Multidecadal Oscillation in the low-frequency variation of extreme high temperature in the Northern Hemisphere

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Abstract: The frequency and intensity of extreme high temperature (EHT) in the Northern Hemisphere exhibit remarkable low-frequency (LF) variations (longer than 10 years) in summer during 1951–2017. Five hotspots featuring large LF variations in EHT were identified, including western North America–Mexico, eastern Siberia, Europe, central Asia, and the Mongolian Plateau. The probability density functions show that the higher EHT occurrences over these hotspots in recent decades is consistent with the shifted average and increased variances in daily mean temperature. The common features of the LF variation in EHT frequency over all domains are the remarkable increasing trends and evident decadal to multidecadal variations. The component of decadal to multidecadal variations is the main contribution to the LF variations of temperature in the last century. Further analysis shows that the coherent variability of decadal to multidecadal temperature variations over western North America–Mexico, eastern Siberia, Europe, and the Mongolian Plateau are the footprints of a dominant natural internal signal: the Atlantic Multidecadal Oscillation. It contributes to the variations in temperature over these hotspots via barotropic circumglobal teleconnection, which imposes striking anomalous pressure over these regions. This study implies that natural internal variability plays an important role in making hotspots more vulnerable to EHT.

Keywords: *Extreme high temperature, decadal-multidecadal variation, Atlantic Multidecadal Oscillation*

Dynamic simulation of the two-way interaction between flooding and land-use change to better understand and reduce future flood risk

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Abstract: Flooding is one of the costliest natural hazards of today, with an estimated damage of US$56 Billion in 2016. With climate change and the ongoing urbanization of floodplains, flood events are likely to cause more damage in the future. Consequently, in order to understand future flood risk and the effectiveness of various risk reduction strategies, it is important to understand how flooding, the number of people and assets exposed to this flooding and the vulnerabilities of these people and assets could evolve into the future under different climate and socio-economic scenarios. Changes in land-use play a key role in this. This is because land-use changes not only affect flooding (due to changes in the amount of rainfall that is converted to runoff and the speed with which floods propagate through the landscape), but because the resulting flooding can in turn also affect future changes in land use (due to land use planning to reduce flood risk and behavioral responses to move away from flood prone areas). Consequently, there is a two-way interaction between changes in flood risk and changes in land use.

This research develops a simulation model that takes the dynamics of the two-way interaction between changes in land use and changes in flooding into account. This is achieved by loosely coupling a Land-Use Cellular Automata (LUCA) model with a 2-D hydrodynamic flood model, where the changes in land use, simulated using the LUCA model, result in changes in the surface properties in the flood model, and hence the extent of flooding. Similarly, the flood extent obtained from the flood model can be used to identify areas at risk of flooding, which can then be translated into land use planning strategies. These can involve the restriction of development in flood prone areas or encouraging growth in low risk areas, the impacts of which are then simulated in the LUCA model, impacting on which areas will be flooded in the future. Such a linked model facilitates risk-informed adaptation planning and decision-making, enabling effective risk reduction strategies to be developed and the evolution of flood risk under different plausible futures to be communicated to a range of stakeholders.

The linked LUCA-flood model is applied to the Gawler River catchment to the north of Adelaide, South Australia. The catchment covers an area of 600km² and cuts across six different local government areas. On average, the catchment floods on average every 10 years, and in 2016, flooding in the catchment caused $50 Million in damages. Land use changes under different socio-economic drivers are simulated using the LUCA model Metronamica and flood extend is modelled using the 2-D hydrodynamic flood model Mike-Flood. The impact of including the two-way interaction between land use change and flooding is tested for a number of scenarios, including scenarios with different approaches to flood risk reduction such as structural mitigation and land use planning. In each scenario, the total simulation time period considered is 30 years (from 2016 to 2046), with changes in the flood model as a result of changes in the LUCA model, and changes in the land use planning policies as a result of the flood risk obtained from the Mike model, being made at ten year intervals. The differences in flood risk obtained by ignoring and including the two-way interaction between land use change and flooding are based on average annual loss, which is calculated as part of an impact assessment, based on the concept of the risk triangle combining hazard, exposure and vulnerability.

The results obtained indicate that consideration of the two-way interaction between land use change and flood impact can have significant impact on levels of risk. This highlights the potential dangers associated with ignoring this interaction when simulating the evolution of flood risk and the effectiveness of different risk reduction options into the future.

Keywords: *Future flood risk, flood-land use change interaction, dynamic exposure, flood risk reduction*

Risk assessment of geological disasters in the Hehuang valley of the Qinghai-Tibet Plateau

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Abstract: The Yellow River and Huangshui valley,located at the northeast margin of the Qinghai-Tibet Plateau, are prone to geological disasters due to violent geological activities, large elevation difference and strong hydraulic power.

Based on the disaster-bearing characteristics of geological disasters (collapse, landslide, debris flow) in Hehuang valley, this paper constructs an evaluation index system by selecting geomorphology, slope, slope height, vegetation, lithology, rainfall, distance from faults, rivers and roads and other factors, and using information quality model to calculate the risk index of collapse, landslide, debris flow and its comprehensive geological disaster risk index, and the risk of geological hazard in the study area was divided into extremely high, high, medium, low and very low areas.

The results show that the extremely high risk areas are mainly located in the valley(town)area, accounting for 7.56%, including the middle and lower reaches of the Yellow River and Huangshui river in Guide county, Huangzhong county and Ledu county. The high risk areas are mainly located in small and medium undulating mountain basins, accounting for 21.2%, including Huangzhong county, Minle county, most areas of Pingan district, south of Datong county, southwest of Huzhu county, surrounding areas of Xining and central areas of Ledu county. The middle danger areas are mainly located in the middle undulating mountain areas, accounting for 23.45%, which belongs to the transition areas of high and low danger area. The low risk areas are mainly located in large and medium undulate mountain areas,accounting for 42.1%, including most areas of Haiyan county, central and western Huangyuan county, northwest of Datong county, Jianzha county, south of Guide county and southeast of Tongren county. The extremely low risk areas are mainly located in the extremely high mountains such as Lenglong mountain, Laji mountain and Western-leaning mountain, accounting for 11.23%, including northeast and southwest of Menyuan county, Haiyan county, southwest of Tongren county, the junction of Ledu county, Minhe county and Hualong county, as well as the central and western parts of Jianzha county. This study is of great significance to the disaster prevention and reduction of Hehuang valley and the sustainable development of society.

Keywords: *Geological disasters, harmfulness, Hehuang Valley, information quality model*

Exposure Analysis of Highways Network in China on the Context of Future Extreme Precipitation Scenarios of CMIP5

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Abstract: With the aggravation of global climate change, how to deal with the potential extreme weather events, especially extreme precipitations, has become a frontier issue in research. China experienced a high-speed growth of high infrastructure in recent decades. As the backbone socio-econ development, highway infrastructure is exposed to more severe precipitations and induced secondary hazards, e.g. landslide and debris flow, causing seriously structural and functional damage. Exposure assessment of highway system under future extreme precipitation scenarios is a vital task in the decision making of climate adaptation and disaster risk reduction measures. Future Extreme Precipitation Scenarios are based on the results of historical climate simulation and the extreme precipitation climate projections under two representative concentration pathways (RCP4.5 and RCP8.5) of 21 global climate models in the phase 5 of the International Coupled Model Comparison Programme (CMIP5). Extremum theorem and quantile regression method are applied to calculate extreme precipitations at different time scales, such as the precipitation in one day and three consecutive days. The analysis results show that the frequency and intensity of extreme precipitations will increase in the future, and there are significant spatial variation in extreme precipitations in China. The extreme precipitations are over 100 mm, and means of extreme precipitations nationwide increase by 3-5 mm per year. The maximum monthly precipitations are concentrated in January, June, July and December, spatially clustered in Guangdong and the junction of Anhui, Hubei and Jiangxi provinces. The highway exposure assessment is based on the data from the Openstreet Maps and extreme precipitation scenarios, considers the different types of infrastructure (road segments and intersections). We evaluate both the topological and the functional characteristics of the highway in hot zones under extreme scenarios, combining the cohesion, maximum connected subgraph and network efficiency factors and other complex network indicators. The results show that the exposures of highways in areas with extreme precipitations will increase steadily in the future. Assuming an invariant highway infrastructure network, more than 10,000 kilometers and 4,000 intersections are exposed to extreme precipitations, accounting for about 20% of the total exposed nodes. Most functional indicators of China's highway network will not change significantly in the future, while the negative impact in hot zones with extreme precipitations will escalate. With the increasing exposure to extreme events, more targeted disaster risk reduction measures are in great need, especially in the identified high-impact areas.

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Keywords: *Extreme precipitation events, highway, complex network, exposure analysis*

Effects of horizontal resolution on the hourly precipitation in AGCM simulations

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Abstract: To analyze the effects of horizontal resolution on hourly precipitation, four Atmospheric Model Intercomparison Project style simulations are carried out using the Chinese Academy of Sciences Earth System Model (CAS-ESM) and the Community Earth System Model (CESM) during 1998-2016. The simulations include CAS-ESM at resolutions of 1.4° latitude × 1.4° longitude (CAS-ESM L) and 0.5°× 0.5° (CAS-ESM H), and CESM at resolutions of 1.9° latitude× 2.5° longitude (CESM L) and 0.47°× 0.63° (CESM H), respectively. We focus on the frequency of model-simulated hourly precipitation and assessed the factor with respect to high-resolution satellite observations and reanalysis. Although neither CAS-ESM H nor CESM H show systematic improvements of measurable precipitation (>0.02 mm h-1) frequency, noticeable improvement of heavy rainfall (>2 mm h-1) frequency is demonstrated in the high-resolution experiments during all seasons over land and ocean. The zonal mean, seasonal mean and area-weighted average frequency support the above results. The high-resolution experiments outperform the low-resolution experiments in reproducing intensity and amount of hourly precipitation. The added values are apparent in heavy precipitation intensity from CAS-ESM H and CESM H. Over the monsoon regions and tropical convergence zones, the patterns of probability density functions for precipitation from high-resolution experiments are closer to the observations and reanalysis than those from the low-resolution simulations. The increasing large-scale precipitation and reasonable integrated water vapor flux contribute to the improvements in hourly precipitation characteristics. The results of this study support the concept that high-resolution global simulations could produce improved hourly precipitation capabilities, especially for heavy rainfall on both global and regional scales.

Keywords: *Horizontal resolution, characteristics of hourly precipitation, Earth System model, AMIP simulation*

River floods induced population mortality risk across the globe

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Abstract: Casualties and economic losses caused by river floods are substantial and rising in the context of climate change. Assessing the population mortality risk to river floods in the future is critical to disaster prevention and mitigation. Based on the projection of the climate (the representative concentration pathways (RCPs)) and the population (the Shared Socioeconomic Pathways (SSPs), this paper focuses on the population mortality risk of the river floods on the globe scale in 2030s (2016-2035) and 2050s (2046-2065). First we obtained the annual death tolls in different scenarios combinations (RCP4.5-SSP2 and RCP8.5-SSP3) on the grid, country and continental scale by using an available inundation dataset, a vulnerability function and population data. Then we used the Emergency Events Database's historical disaster data to calculate the adjustment coefficient K on the continental scale. Finally, we discussed the uncertainty of the results at different scales. The results show that (1) global average annual death toll will be ~17 k under RCP4.5-SSP2 and increase 7% under RCP8.5-SSP3 during 2030s; it will be ~23 k under RCP4.5-SSP2 and increase 47% under RCP8.5-SSP3 during 2050s. (2) High-risk areas are in Southeast Asia and South America along large deltas. There are nine high-risk countries, accounting for more than 50% of the risks. (3) The inundation data performance of each model is uneven. Globally, the resulting uncertainties are higher under RCP4.5-SSP2 than RCP8.5-SSP3 during 2030s, and the inverse situation occurs during 2050s.

Keywords: *River floods, population mortality risk, global scale*

A consensus by integrating multiple research conclusions on the future crop yields by climate change in China

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Abstract: Many researches have shown that climate change has a significant impact on crop yield in China, but their results are many differences. What is the consensus from these multiple conclusions is the attention of this paper. By adopting the systematic article search and screening (SASS) method and setting selection criterion, we have constructed 737 conclusions data sets, which obtained from more than a thousand articles with the theme. Then we use likelihood scale and trend analysis methods to quantify the consensus level and uncertainty interval of these conclusions. The results show that: (i) Crops yield have declined significantly in the future, maize and rice yields declined the most in Northeast, change about -17.2% and -13.3% respectively, while wheat yield in the Northwest is the most obvious, with -7%. (ii) Crops yield decrease the second half of 21st century is higher more than 5% than that in the first. And the most affected crop by climate change is maize with exceed -25%, followed by rice and wheat with exceed -10% and -5%, at the end of this century. (iii) The positive impact of CO2 factor on crops yield change nearly 10%. Our conclusions clarify the consensus of multiple conclusions, which is useful for excluding disagreement on conclusions and examining the policies and actions of crop yield change that China has taken and should take in response to climate change.

Keywords: *Climate change, yields risk, consensus, China*

Population exposure to droughts due to future climate and socioeconomic change in China under the 2.0 ^{o}C global warming target

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Abstract: The Paris Agreement proposes the target that holding the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change. Studying the population risk to droughts under this 2°C target will be helpful in guiding new policies that mitigate and adapt to disaster risks under climate change. Risk is often represented as the probability of occurrence of hazardous events or trends multiplied by the impacts if these events or trends occur, it results from the interaction of hazard, exposure, and vulnerability. Therefore, exposure assessment is one of the most important aspect of disaster risk assessment. Exposure usually refers to the presence of people, livelihoods, species, or ecosystems; environmental functions, services, and resources; infrastructure; or economic, social, or cultural assets in places and settings that could be adversely affected.

Based on simulations of five global climate models (GCMs) from the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP), the Standardized Precipitation Evapotranspiration Index (SPEI) was used to calculate drought frequencies in the reference period (1986–2005) and 2°C global warming scenario (2040–2059 in RCP4.5). Then population exposure was evaluated by combining drought frequency with simulated population data from shared socioeconomic pathways (SSPs) consistent with the RCPs, taking into account the geographic change in the distribution of population. In addition, the relative importance of climate and demographic change and the cumulative probability of exposure change were analyzed.

Results revealed that population exposure to droughts in the east of China is higher than that in the west; exposure in the middle and lower reaches of the Yangtze River region is the highest, and it is lowest in the Qinghai-Tibet region. An additional 13.02 million people will be exposed to droughts under the 2.0°C global warming scenario relative to the reference period. Population change is the primary contributor to exposure in the 2.0°C global warming scenario, more than climatic change or the interactive effect. Of the three drought intensities – mild, moderate, and extreme – moderate droughts contribute the most to exposure. Probabilities of increasing or decreasing total drought frequency are roughly equal, while the frequency of extreme drought is likely to decrease in the 2.0 C global warming scenario. The study suggested that reaching the 2.0 C target or a more ambitious target is a potential way for mitigating the impact of climate change on both drought hazard and population exposure.

Keywords: *Drought, socioeconomic exposure, climate change, RCP scenarios, SSP scenarios*

Analysis on Change Trend of extreme temperature events in Qinghai-Tibet Plateau based on probability distribution

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Abstract: Extreme climate events are a hot issue in the world because of their great influence on nature and economic society. Qinghai-Tibet Plateau, it is one of the most sensitive areas where is response to the global climate change. What is happening to regional extreme temperature events in the context of global warming? Based on the temperature data of 78 meteorological stations in Qinghai-Tibet Plateau in 1961-2015 years, the extreme temperature events of 78 meteorological stations were extracted. The temporal and spatial manifestations of extreme temperature event frequency and intensity in Qinghai-Xizang plateau are analyzed. Based on the principles of unity, similarity and spatial continuity of a natural geographical unit, this paper analyzes the difference of probability distribution in different regions. The main conclusions are as the follows:

1. On the temporal-spatial, the sites with less frequency of extreme high temperature events are mainly distributed in the southern part of the plateau, and the sites with more frequency of extreme hypothermia are mainly distributed in the northern region of the plateau. The intensity of the weak extreme high temperature events mainly occurred in the southern part of the plateau, and the high extreme temperature event intensity mainly occurred in the large area of the southern Plateau. The frequency and intensity of extreme high temperature events in most sites increase, and the frequency and intensity of extreme hypothermia events weaken.
2. In the extreme temperature event frequency, the Hengduan Mountains and Zoige Plateaux in the Qinghai-Tibet Plateau have the greatest response to climate warming, both in extreme high temperature events and in extreme hypothermia events, both of which are of the highest degree and degree of weakening. The response to climate warming in the Yellow River-Huangshui River Valley is unique, and it is the only area in the plateau that is shown as an enhanced trend in extreme cold events.
3. In the intensity of extreme temperature events, the regions with higher degree of climate warming affecting extreme high temperature events are mainly located in the north of Kunlun Mountains, while the influence of extreme hypothermia events is mostly distributed in the area south of Kunlun Mountains. The Himalaya area and Yellow River-Huangshui River Valley are unique, and in the extreme high temperature event, the Himalaya region is the only one which shows a weakening trend, which is inconsistent with its frequency change characteristics. In the case of extreme hypothermia, the Yellow River-Huangshui River Valley is the only region that shows an enhanced trend, which is similar to its frequency characteristics.

Keywords: *Qinghai-Tibet Plateau，probability distribution，extreme temperature events，change-character*

Impacts of changes in climate mean, variability, and their interaction on wheat yield risk on the North China Plain

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Abstract: An understanding of global change risk to food insecurity requires measuring the influence of climate change not only on the future variation of mean crop yield but also on the variability and extremes of crop yield. In this study, the future changes in wheat yield risk components (mean, interannual variability, and the lower extreme) were evaluated, and the contributions of climate change components (changes in mean, variability, and their interaction) were disentangled on the North China Plain (NCP). In wheat yield simulation experiments with control groups, the Crop Environment Resource Synthesis model for wheat in the Decision Support System for Agro-technology Transfer with multiple general circulation model ensembles under two representative concentration pathways (RCPs 4.5 and 8.5) was used to derive estimates. Wheat yield risks increased on the NCP in the future under RCPs 4.5 and 8.5, with the yield mean reduced by approximately 10% and 20% and the lower yield extreme by 5% and 20%, in spite of favourable reductions in yield variability by 15% and 18%, respectively. When disentangled, the changes in climate variability and in the interaction of climate mean and variability together explained 51–75%, 32–49%, and 47–65% of the changes in yield mean, variability, and lower extreme, respectively. The change in climate mean was the second largest contribution to the changes in yield mean and lower extreme, with 15–44% and 10–42%, respectively. These results highlight the importance of considering the changes in climate variability and in the interaction of variability with the climate mean on crop yield impact and risk analysis. The projected increasing frequency of low yield extreme years should also remind the Chinese government to include grain reserve system adjustments in addition to adaptations against higher temperatures as a part of the agricultural adaptation policy to climate change.

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Keywords: *Wheat yield risk, climate change, contribution analysis, DSSAT, North China Plain*

Modulation of the Kara sea ice variation on the ice freeze-up time in Lake Qinghai

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Abstract: Lake ice phenology, as an indicator for climate variability and change, exerts a great influence on regional climate and hydrometeorology. In this study, the changing characteristics of lake ice phenology at Lake Qinghai (LQH) are investigated using retrieved historical datasets during 1979-2016. The results show that the variation in freeze-up date over LQH is characterized by strong interannual variability. Further analysis has revealed that November Kara sea ice concentration (SIC) variation can advance the freeze-up date at LQH. During the low sea ice years, the open sea serves as a strong diabatic heating source, largely contributing to the enhanced Arctic Eliassen-Palmer flux, which then results in the deceleration of zonal wind in mid-high latitudes. In addition to this, accompanied with the decreasing Kara SIC, the enhanced stationary Rossby wave flux propagation along the high-latitudes regions may further exert remarkable influences in deepening the East Asian trough, which provides a favorable atmospheric circulation pattern for cold air intrusion from the Arctic and Siberian regions to mainland China. The decreased surface air temperature would thus advance the freezing date over LQH. Furthermore, the close relationship between atmospheric circulation anomalies and Kara SIC variations is validated by a large ensemble of simulations from the Community Earth System Model, and the atmospheric circulation patterns induced by the SIC anomalies are reproduced to some extent. Therefore, the November Kara sea ice anomaly might be an important predictor for the variation in the freeze-up date at LQH.

Keywords: *Arctic sea ice, lake ice phenology, CESM, climate change*

Projected near-term changes of temperature extremes in Europe and China under different aerosol emissions

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Abstract: This study assesses near-term future changes in temperature extremes over China and Europe in scenarios with two very different anthropogenic aerosol (AA) pathways from 2016 to 2049: a maximum technically feasible aerosol reduction (MTFR), and a current legislation aerosol scenario (CLE), both with greenhouses gas forcing following RCP 4.5. Simulations with a fully coupled atmosphere-ocean model HadGEM3-GC2 show that there is an increase in hot extremes and a decrease in cold extremes relative to the present day (1995-2014) over China and Europe in both scenarios. However, the magnitude of the changes in both hot and cold extremes depends on the AA pathway. The AA reduction in MTFR amplifies the changes in temperature extremes, relative to CLE, and accounts for 40% and more than 30% of the changes in temperature extremes over China and Europe respectively under the MTFR scenario.

The changes in temperature extremes depend on the increase in seasonal mean surface air temperatures to a large extent. The summer surface warming over eastern China induced by a reduction in AA are associated with positive changes in clear-sky shortwave (SW), which arise through aerosol-radiation interaction. In contrast, summer surface warming and changes in hot extremes over Europe due to a reduction in AA occur via positive changes in SW cloud radiative effect, which are mainly due to aerosol-cloud interactions and positive atmosphere-land feedback. The reduction in AA leads to an increase of water vapor in the atmosphere due to positive sea surface temperature anomalies over western Pacific and North Atlantic in both summer and winter, leading to positive changes in clear-sky longwave at the surface and warming over Eurasia, inducing changes in both hot extremes in summer and cold extremes in winter.

Keywords: *Temperature extremes, a current legislation aerosol scenario, a maximum technically feasible aerosol reduction*

New understanding of climate change on the Qinghai-Tibetan Plateau and its adapting counter-measures

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Abstract: Climate changes in its mean, variability, and extremes, exhibiting obviously spatial-temporal difference. As the "Third Pole" (TP) of the world, the Qinghai-Tibetan Plateau (QTP, abbreviated also as TP for simplicity) plays crucial roles of source and sink of global warming. Global climate change has mainly influenced the climate on the TP and also its glaciers, snow lines, permafrost and ecological systems. Most part of the TP has been getting warmer and wetter, with increased frequency of night-time rainfall, and increased carbon sink. Small part of the TP has become warmer and drier, with decreased carbon sink. The key countermeasure to adapt to climate change on the TP is to develop ecological industry cluster, including carbon-trade, high plateau national park (tourist and sight-seeing industry), health care industry, green animal husbandry, etc.

Keywords: *The Qinghai-Tibetan Plateau, climate change, ecological system response, ecological industry cluster*

Assessing the exposure of global industrial system

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Abstract: We assessed the exposure of global industrial system under different climate scenarios. Three steps were adopted to assess the exposure. First, we mapped the industrial output value using night-time light images. Second, we modelled the global land use changes using CA model. Last, we forecasted the changes in industrial output value and assessed the global exposures of global industrial under Rcp 4.5 scenario. It was found that for the exposure of extreme precipitation, the highly exposed areas of industrial system is concentrated in Japan and South Korea. In the future, the exposure of the industrial economic system in the Yangtze River Delta and Pearl River Delta of China, India, Bangladesh and Italy will increase significantly. The high-exposure areas under extreme high temperatures are concentrated in the southern United States. In the future, the exposure of the industrial economic system in the Pearl River Delta region of China, Egypt, India and Southeast Asia, and China will increase.

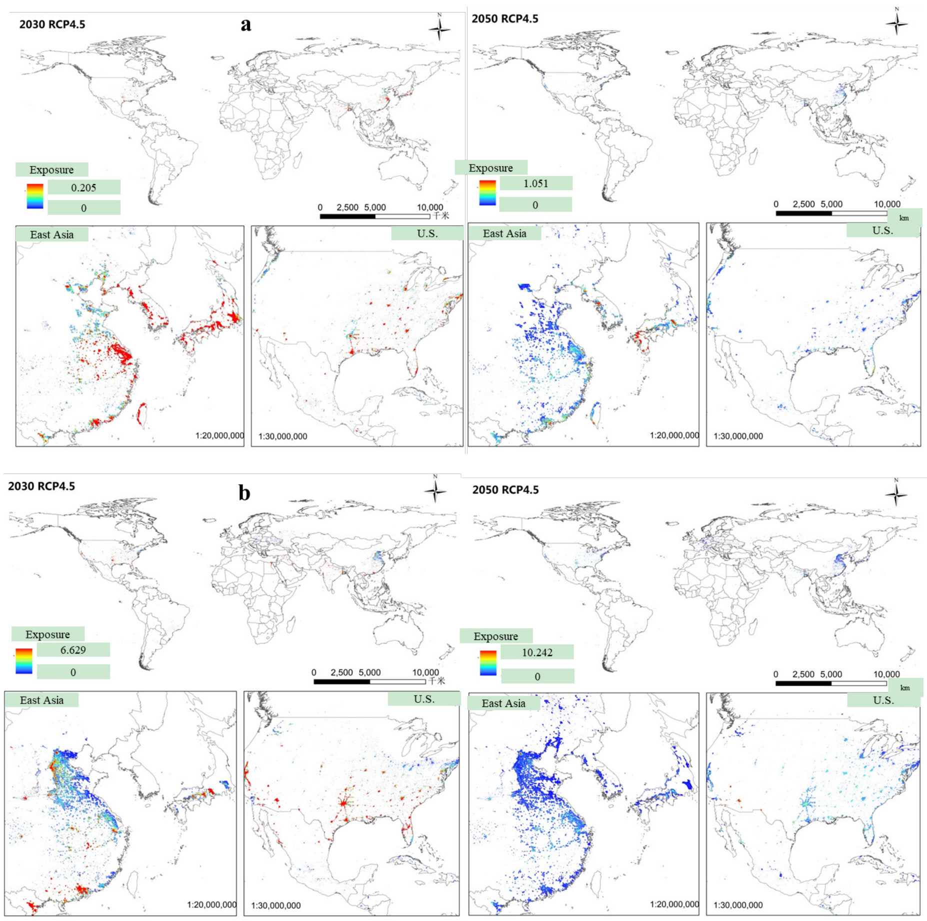

Figure 1. Exposure of global industrial system facing extreme precipitation (a) and high-temperature during 2030-2050 under RCP 4.5

Keywords: *Climate change, risk, exposure, global industrial system*

Rainfall statistics, stationarity, and climate change

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Abstract: There is a growing research interest in the detection of changes in hydrologic and climatic time series. Stationarity can be assessed using the autocorrelation function, but this is not yet common practice in hydrology and climate. Here, we use a global land-based gridded annual precipitation (hereafter P) database (1940–2009) and find that the lag 1 autocorrelation coefficient is statistically significant at around 14% of the global land surface, implying nonstationary behavior (90% confidence). In contrast, around 76% of the global land surface shows little or no change, implying stationary behavior. We use these results to assess change in the observed P over the most recent decade of the database. We find that the changes for most (84%) grid boxes are within the plausible bounds of no significant change at the 90% CI. The results emphasize the importance of adequately accounting for natural variability when assessing change.

The formal approach to evaluating whether a time series is stationary begins with an inspection followed by analysis of the autocorrelation function. We use one of the longest instrumental records of annual P—the 244-y (1767–2010) record from the Radcliffe Observatory site at Oxford, United Kingdom. We first estimate the autocorrelation of the time series for lags from 0 to 80 y. The result shows that the autocorrelation for most lags $\geqslant 1$ is statistically indistinguishable from 0. We calculate the averages over climatic timescales: the commonly used 30-y period as well as a 10-y period. The results show the average changes from one period to the next, while the overall time series remains stationary. In summary, the long-term Radcliffe Observatory annual P data reveal a record that is more or less indistinguishable from a random process. To examine this issue more broadly, we use the gridded monthly precipitation database from the Global Precipitation Climatology Center (GPCC) Version 5 Autocorrelation of Global Land-Based Precipitation. Results showed that the annual P was indistinguishable from a random process over most (~76.3%) of the global land surface. In fact, the randomness typical of P time series as reported here means that one may have to wait at least a human lifetime before being confident about a statistically significant change in P. That makes it even more important for hydrologists and climate scientists to rigorously incorporate the variance into assessments of changes in P.

Keywords: *Precipitation, stationarity, variance*

The dependence of daily and hourly precipitation extremes on temperature and atmospheric humidity over China

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Abstract: Precipitation extremes are expected to increase by 7% per degree of warming according to the Clausius–Clapeyron (CC) relation. However, this scaling behavior is inappropriate for high temperatures and short-duration precipitation extremes. Here, daily data from 702 stations during 1951-2014 and hourly data from 8 stations during 2000-2015 are used to examine and explain this behavior in China. Both daily and hourly precipitation extremes exhibit an increase in temperature dependency at lower temperatures. The CC scaling transitions from positive to negative rates with temperatures greater than 25°C. Unlike the increase in daily data, which is similar to single-CC (1CC) scaling, the increase in hourly data resembles super-CC (2CC) scaling for temperatures greater than 13°C. Results show that the precipitation extremes are controlled by water vapor for a given temperature. At lower temperatures, precipitation extremes exhibit a positive linear dependence on daily actual vapor pressure which value is almost equal to saturated vapor pressure at a given temperature. At higher temperatures, actual vapor pressure has difficulty maintaining a consistent increasing rate as the exponential increasing of saturated vapor pressure. Higher temperatures result in larger vapor pressure deficits, which lead to sharply decreases in precipitation extremes. Similar scaling behaviors are obtained in 10 river basins over China, where breaking point temperature increases from 17°C along the northwest inland to 25°C along the southeast coast. These behaviors demonstrate that precipitation extremes are firmly linked to temperature when there is sufficient moisture at lower temperatures and limited by insufficient moisture at higher temperatures. Overall, precipitation extreme events require more attention in a warming climate.

Keywords: *Precipitation extremes, temperature, atmospheric humidity, daily and hourly*

Statistical and dynamical downscaling of temperature extremes in China

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Abstract: Climate change induced by anthropogenic emissions of greenhouse gasses has a great impact on climate extremes, which influence not only socioeconomic activities but also natural processes and human being. Because the global climate models (GCMs) usually have coarse horizontal resolution (typically 50-200 km) and their simulations are insufficient to represent the climate extremes in local/regional scales, both statistical and dynamical downscaling methods are widely used to improve temporal and/or spatial distributions of GCMs simulations. In this presentation, we firstly investigate the temperature extremes at a horizontal resolution of 25km in China from both statistical (based on the Bias Correction Spatial Disaggregation--BCSD) and dynamical (based on WRF and RegCM models) downscaling methods. The results indicate that both downscaling methods show the satisfactory capability in representing the spatiotemporal characteristics of temperature extremes over most regions in China. Compared with observation, two methods tend to underestimate the trends of temperature extremes. Moreover, RegCM generally performs better than that WRF in reproducing the mean temperature extremes, especially at the Tibetan Plateau, while WRF shows better performance in the reproduction of the interannual variability of extreme temperature indices in China.

Then, we apply the BCSD method on the future simulations under RCP 2.6 during 2006-2050 from the Model for Interdisciplinary Research on Climate version 5 (MIROC5) in the CMIP5 project. The MIROC5 is selected because of its relatively better performance in representing the historical temperature extremes). Compared to raw CMIP5 products, we find that WSDI and TX90 frequency decrease in both Tibetan Plateau and the south and of China, where TX10 intensity increases. Furthermore, the BCSD method results in a lower (higher) probability of temperature extreme in boreal spring (autumn) due to its effects on their mean values. Moreover, BCSD leads to a reduction in the increasing trend in both WSDI and TX90 frequency in the south of China, but an increase in their trends in the northeast China.

From our research, the BCSD statistical downscaling method can provide high temporospatial and value-added climate products, which facilitate to be used in various applications such as climate extremes investigation and hydrological/land surface model forcings. Besides, compared to the dynamical downscaling based on regional climate models, the BCSD method requires low computation resources and is high efficiency. Thus, we strongly recommend to apply the BCSD method in the regional and global downscaling applications.

Keywords: *Statistical downscaling, dynamical downscaling, temperature extremes, China*

Extreme temperature and precipitation changes associated with four degree of global warming above pre-industrial levels

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Abstract: Currently, most research has concentrated on warming levels of 1.5 °C and 2 °C relative to the pre-industrial levels. However, the climate system is very complicated, and thermal inertia plays a vitally important role in climate change. As such, in addition to the 1.5 °C and 2 °C warming levels, higher levels of temperature increases should also receive more attention. In 2012, the World Bank released a report and stated that a 4 °C increase in global temperature relative to the pre-industrial levels would be devastating. However, there is a lack of scientific literature on the changes in climate associated with a 4 °C temperature increase. Based on the daily temperature and precipitation data from the Coupled Model Intercomparison Project Phase 5 (CMIP5), we project the global terrestrial changes in the extreme values of temperature and precipitation in association with a warming of 4 °C above the pre-industrial levels using the Representative Concentration Pathways 8.5 (RCP8.5) scenario. The results indicated that cold extremes will decrease and warm extremes will increase. More remarkable signals in temperature extremes based on daily minimum temperature are expected, and local changes in temperature extremes generally extend beyond the natural internal variability. Significant signals in the frequency of temperature extremes appear in low latitudes, while the temperature changes of the coldest and hottest days are great in northern high latitudes. Large signal-to-noise ratios for warm extremes mainly occur in low latitudes, while those of cold extremes are not uniformly distributed. Specifically, the average signal-to-noise ratio (S/N) for the warmest day (TXx), the coldest night (TNn), cold nights (TN10p), cold days (TX10p), warm nights (TN90p), warm days (TX90p), frost days (FD), tropical nights (TR), and growing season length (GSL) over land is 3.9, 4.3, –2.6, –2.6, 8.7, 7.2, –2.2, 7.0, and 2.0, respectively.

Precipitation extremes are expected to intensify, particularly for R95p. Signals in high-precipitation extremes are prominent in high latitudes and usually exceed the local natural internal variability. Changes in extreme dry events are high in the extra-tropics and generally lie within the background noise. Compared with the temperature extremes, local changes in the precipitation extremes are usually smaller than the background noise, with the global mean S/N value of 1.0, 0.6, 0.1, 0.9, and 0.6 for very wet-day precipitation (R95p), the maximum 5-day precipitation (RX5day), consecutive dry days (CDD), simple daily intensity (SDII), and total wet-day precipitation (PRCPTOT), respectively.

The inter-model uncertainty in the projection of warm extremes is larger than that of the cold extremes. At the large scale, the inter-model uncertainty of the high-precipitation extremes and TN10p and TX10p is generally small in the regions with great signals, while the opposite trend exists for the other temperature extremes and the extreme dry events.

Of particular importance is that the changes in all local temperature extremes are generally greater than the natural internal variability, and local changes in the precipitation extremes are usually smaller than the background noise at 4 °C global mean temperature increase above pre-industrial levels. Relative to the 1.5 °C global warming scenario, there would be more violent temperature and precipitation extremes with the 4 °C warming level, and these extremes would pose more threats to natural and human systems.

Keywords: *Climate extremes, 4 °C global warming, signal-to-noise ratio, inter-model uncertainty*

Hot spots of climate extremes in the future

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Abstract: A Regional Extreme Climatic Change Index (RECCI), simultaneously considering the changes in intensity, frequency and interannual variability of three major extreme climatic variables (i.e., precipitation, temperature and wind speed), is constructed to represent regional changes of climate extremes in response to global warming. First, the daily outputs from 13 models in the Coupled Model Intercomparison Project phase 5 project in both historical and future simulations under the Representative Concentration Pathway 8.5 scenario are used to compute the extreme climatic indices. Second, the RECCI is computed on both annual and seasonal time scales during three periods (i.e., 2016–2035, 2046–2065 and 2080–2099) over 26 subregions.

The spatiotemporal change of the RECCI is investigated, and then, the 26 subregions are classified into four categories for each period. The first category with the largest RECCI value is very sensitive to global warming, which is called hot spots of climate extremes. The results show that most hot spots are not time invariant on annual and seasonal time scales with some exceptions.

On the annual time scale, the Amazon Basin is the only persistent hot spot in all three periods. For the seasonal time scale in March-April-May, the climate extremes in the Amazon Basin always display the strongest responsiveness to global warming, and the Eastern Africa is the only persistent hot spot in June-July-August in three periods. Similar results are also found for the other two seasons and periods. In addition, the change in extreme temperature is crucial over the East Asia with change in frequency prominent.

Keywords: *Climate extremes, hot spots, RECCI*

Reduced livestock snow disaster risk in the Qinghai-Tibetan Plateau: contribution from climate change and socioeconomic development

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Abstract: Livestock snow disaster (LSD) is a serious winter weather threat in pastoral areas, where the deep snow, severe cold, and other conditions render forage unavailable or inaccessible, thus leading to high livestock mortality. Such disaster events occur widely in the semi-arid regions of Eurasia steppes from northern northeast China to central Asia, and in alpine steppes such as the Qinghai-Tibetan Plateau (QTP), where they have claimed severe historical losses. Moreover, the changing climate is likely to bring considerable uncertainty in the vegetation and winter precipitation regimes of these regions. Not surprisingly, future challenges to snow disaster reduction and adaptation to the changing climate in these regions are of great concern. Given the practical need for risk-informed adaptation, efforts are needed to quantify present-day and future livestock snow disaster, and disentangle the relative contribution of climate change and socioeconomic development.

In this study, we focused on the livestock snow disaster in the QTP, the highest and one of the largest natural pastoral areas in China and the world. Based on historical snow disaster event records, generalized additive models and machine learning algorithms were employed to quantify the relationship among livestock mortality, snow hazard intensity, seasonal environmental stressors and prevention capacity. An event-based probabilistic risk assessment framework for LSD capable of accommodating changes in snow hazard intensity, environmental stressors, and prevention capacity was developed. Applying the framework, historical (1980-2015) distributions LSD risk was derived. Our results showed overall reduced livestock snow disaster risk in the QTP region. Historically, annual mortality reduced by 7.9% per year, in which climate change accounted for 1.8 percentage points. LSD risks in the future periods (2016-2065) were projected by incorporating projected climate (representative concentration pathways 4.5 and 8.5) and socioeconomic conditions (shared socioeconomic pathways 2 and 3). Our results indicated that, livestock mortality risk due to snow disaster declines across in the plateau in general in the future, while the spatial pattern of high/low risks did not change much. Both climate warming and increased prevention capacity contributed to the decline in annual mortality risk, but the later dominates the contribution.

***Acknowledgement**: This study was supported by the National Key R&D Program of China (No. 2016YFA0602404), the project of State Key Laboratory of Earth Surface Processes and Resource Ecology, and the Fund for Creative Research Groups of National Natural Science Foundation of China (No. 41621061)*

Keywords: *Integrated modelling, integrated assessment frameworks, conceptual model*

Dependence of tropical cyclone damage on maximum wind speed and socioeconomics

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Abstract: Tropical cyclones (TCs) have devastating impacts and are responsible for significant losses. The potential destruction of a TC is tied to its intensity, proximity and value of vulnerable people and property to the hazard, based on the well-established concept that TC risk is a function of three distinct determinants of hazards, exposure and vulnerability. Consequently, it is essential to diagnose all components of risk in TC-induced direct economic losses (DELs) attribution science. However, researches on quantitative estimation of how TC-induced DELs respond to changes in hazard, exposure and vulnerability are still inadequate. This paper quantifies the relationship between TC-induced DELs with maximum wind speed, asset value and per capita GDP based on the economic concept of “elasticity”, using a regression model with TC records from 2000−2015 for the mainland of China.

First, we establish statistical estimates (including uncertainties) on how sensitive DELs are to changes in these factors through a set of more reliable socioeconomic data. Quantification is performed at the TC level from 2000 to 2015 and exclusively focuses on damage-producing TCs. In addition, we make an additional effort to estimate the regression coefficients using different subsets of the TC records and compare regression models with different variables (e.g. minimum pressure and proportion of non-steel-concrete residential buildings). The coefficients of the three terms indicate that a doubling in maximum wind speed increases the DELs by 179%, a doubling in asset value exposure increases the DELs by 92%, while a doubling in per capita GDP leads to a 59% decrease in DELs when the other two variables are held constant. Besides, the authors also present a series of robustness exercises to demonstrate the reliability of the results.

This research is an effort to connect natural disaster risk (expected DELs specifically) with physical and socioeconomic elements. The results suggest that continuing economic growth will be hard on TC-prone regions, assuming no changes in mitigation and adaptation efforts, and emphasize that human behaviour matters to the formation of disasters and disaster risk reduction. This relationship can be applicable to subsequent TC-induced DELs prediction under climate change and socioeconomic development, and used to inform disaster risk models and disaster risk management.

Keywords: *Tropical cyclones, asset value exposure modelling, direct economic loss attribution*

Predicting global planting suitability of wheat under the 1.5 °C and 2 °C warming goals

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Abstract: Climate change has a significant impact on the suitability of crops, which may have adverse effects on food security. Therefore, it is of great scientific significance to estimate the potential distribution of major food crops under climate change for formulating food production strategies to adapt to climate change. Wheat is one of the food crops with the largest sown area and the highest yield in the world. Although studies have revealed the potential distribution of wheat globally under different climatic scenarios in the future, studies on the potential planting distribution of wheat at the 1.5-degree and 2.0-degree temperature rise levels are still rare. In the present study, we aim to investigate: (1) What is the pattern of potential wheat planting distribution affected by climate change under the 1.5 °C and 2 °C warming? (2) What is the difference between regional distribution?

The MaxEnt is applied in the present study. As a species distribution model (SDM). The principle of the MaxEnt is to relate known models of a species (training samples) with the environmental characteristics of these locations to estimate the response function and contribution of environmental variables and then to predict the potential Geographical range of a species using this relationship. Taking 1986-2005 as the baseline period, which is 0.6°C warmer than pre-industrial period (1850-1900). The warming of 0.9 °C and 1.4°C above 1986-2005 correspond to the internationally accepted threshold of 1.5 °C and 2 °C above pre-industrial. Then, a 30-year moving averages method was used to calculate the period that reaching the specific warming level for the first time. Five GCMs, namely GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, and NorESM1-M are used to assess the impacts of climate change on the distribution and planting suitability of wheat. The training samples which can reflect known locations of wheat is obtained from the Global Harvested Area Fractional for the wheat dataset, The environmental variables are selected based on previous studies and combined with the principle of dominance.

The results of the potential planting distributions of wheat under 1.5°C and 2°C warmer show that the total area suitable for wheat planting in the future did not change significantly. The increase of temperature is beneficial to improve the suitability of wheat planting in middle and high latitudes, while wheat planting in low latitudes is adversely affected.

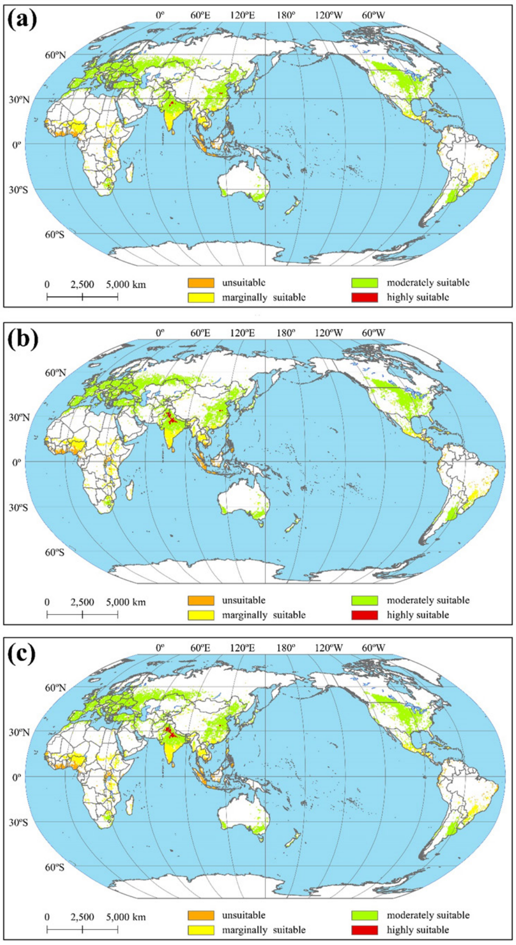

Figure 1. Distribution of Wheat Planting Suitability under Different Warming Goals (a. baseline period, b. 1.5 °C, c. 2.0°C)

Keywords: *World planting suitability of wheat, 1.5 °C and 2 °C warming goals, Maxent model, multi-GCMs ensemble method*

Exploring the relationship between spatiotemporal characteristics of snow cover and ENSO episodes over the Qinghai-Tibetan Plateau

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Abstract: The Qinghai-Tibetan Plateau as a vital water source is the largest area of snow cover in China. Recently, many relative studies presented evidence of a decreasing trend over the Qinghai-Tibetan Plateau snow cover area (SCA) in the last dozen years based on analysis of MODIS snow cover extent product satellite record. The main objectives of this study are to analyze the spatiotemporal characteristics of snow cover over the Qinghai-Tibetan Plateau, as well as to explore the relationship among climate variables and El Niño-Southern Oscillation (ENSO) episodes and SCA used MOD10C2 snow cover production. The SCA was derived from MOD10C2 and analyzing SCA trends through the Mann-Kendall statistical tests. Results indicated that no significant decreasing trend for SCA in the QTP from 2001 to 2016. In addition, trends of SCA over the QTP had spatial differences during the period 2001-2016, SCA of the Southern in the QTP had a decreasing trend while SCA of the Northern had an increasing trend. In the monthly scale, SCA expanded to the lower-altitude areas in the snow-accumulation period (March) while SCA shrunk to the higher-altitude areas in the snow-melt period (August). Generally, there was a negative correlation between decreasing SCA and significant increasing Temperature while a positive correlation between decreasing SCA and decreasing Precipitation. The result of correlation analysis showed that the La Niña years were coincident with larger SCA, while SCA of the El Niño years were lesser than of normal years over the QTP during the period 2001-2016.

Keywords: *Spatiotemporal characteristics of SCA, relationship, ENSO episodes, Qinghai-Tibetan Plateau*

Assessment of future flash flood inundations in coastal regions under climate change scenarios – A case study

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Abstract: Climate change may considerably influence flash floods by increasing extreme precipitation. Coastal regions in eastern and southern China may experience especially negative effects because of the frequent occurrence of tropical cyclones (TCs). This study presented a hazard assessment framework for TCs-induced flash floods under climate change scenarios and assessed future inundations in Hadahe River basin, which is in northeastern China. From 1965 to 2014, there were twenty-four TCs ranging from severe tropical storm to super typhoon over Hadahe River basin in twenty years. General Circulation Models (GCMs) are too coarse to depict the impact of TCs on extreme precipitation; therefore, hourly precipitation data from two gauges and the tracks of TCs were used to assess the impact of TCs. An extreme precipitation event on 3–4 August 2012 and the same 600-year future probabilistic extreme rainfall were utilized to investigate the impact of climate change. Daily precipitation data from eight climate models from the NEX-GDDP dataset during 1965–2005 and 2050–2099 represented historical and future simulation conditions, respectively. The hydrologic model HEC-HMS was integrated with the hydraulic model FLO-2D to simulate discharges and inundations of past and future TCs episodes. The results showed that flooded area is projected to increase by 6.6% and 7.8% for inundation depth between 1.0 and 3.0 m under RCP 4.5 and RCP 8.5 scenarios, respectively. For inundation depth over 3.0 m, flooded area is projected to increase by 17.6% and 22.0%. Relative change of flash flood extent increases as inundation depth increases, indicating that climate change is likely to increase the risk of flash floods. Additional adaptation measures are needed to make the Hadahe River basin and other similar coastal basins more resilient. The results also indicated that considering the impact of TCs produces a more reliable assessment of future flash floods in coastal regions.

Keywords: *Climate change, flash flood hazard, extreme precipitation*

Construction of assessment model of economic impact of natural disaster and its multi-scale applications

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Abstract: The governments around the countries have realized the economic impact is an important component of risk assessment. However, the economic impact includes not only the direct economic loss (DED) caused by the disaster, but also the indirect economic impact (IEI) caused by DED and the transboundary economic impact (TEI) of the disaster area on the other regions outside the disaster area. Based on the mainly limitations of the economic impact assessment, in this paper, we focus on (1) the impact of the labor supply reduction caused by the affected population on the economic system; (2) economic fluctuations in the disaster-affected areas have affected the economic impact of other regions outside the disaster-affected areas.

Therefore, we construct an indirect economic impact assessment model AMIL (Adaptive Multiregional Input-Output with Inventory & Labor) from the basic principles of input-output theory in economics, supplements and improves the composition of the ARIO-Inventory model. It theoretically perfects the interpretation of the disaster model by the assessment model, making the assessment model more comprehensive and the assessment results closer to reality. Finally, the application of the model to the different spatial scales of city scale and global scale has verified the evaluation level of AMIL model constructed in this paper.

The results show that: (1) at city scale, the IEI of the "7.6 Wuhan flood disaster" will underestimate 15.12% if we do not consider labor disruption, and the economic impact in secondary industry accounts for 42.27% of its total impact, while that in the tertiary industry is 36.29%, which will cause enormous IEI if both industries suffer shocks; (2) at global scale, we evaluate the TEI and uncertainties of the US on the world with future annual mean temperature (AMT) raise from 2020 to 2100 are evaluated under RCP4.5. The TEI of the US on the global GDP increases about 4.45 times when AMT rises from 1 to 2°C, that of China increases 4.5 times. The degree to which cold regions benefit from climate change should consider the inhibiting ripple impact from the others. According to multi-scale applications, we hope the AMIL model will provide evidence for the important role of labor disruption and prove that it is a non-negligible component of post-disaster recovery and reduction, and also provide new perspectives and data-based support for regions around the world to cope with climate change and to develop policies by studying the TEI behind international trade.

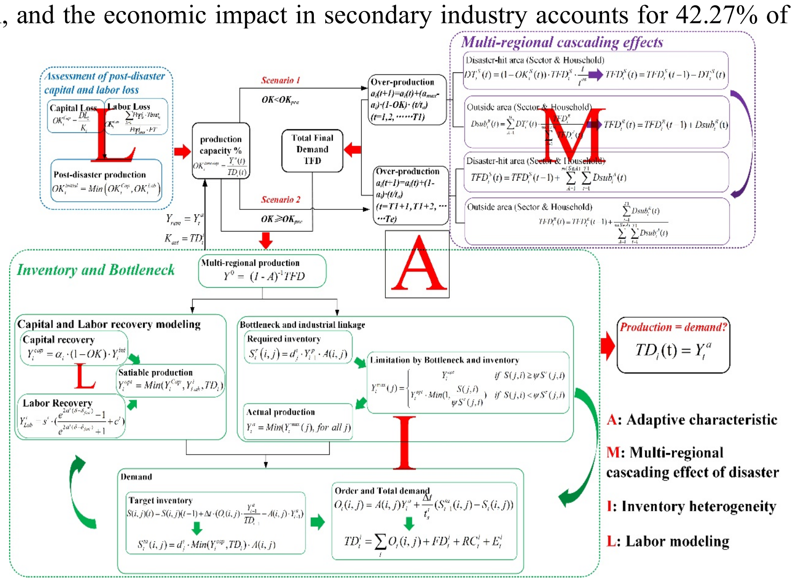

Figure 1. The detailed algorithm flow of the AMIL model

Keywords: *Natural disaster loss assessment, indirect economic loss, Input-Output model*

An integrative investigation of the causation for pre-historical catastrophes in the Lajia Ruins, Qinghai Province, China

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Abstract: Archaeological excavations have exposed a shocking picture of the prehistorical calamities in the Lajia Ruins in the Guanting Basin along the Yellow River. The destruction reasons has been a hot and focus issue in recent years. Geological records of the major disasters in relation to the devastation of this prehistorical settlement were investigated by detailed field observations, sedimentological analysis, Quaternary Geology, Geomorphology and Palaeo flood hydrological analysis. More importantly, we made a comparative study of the conglomerated red clay, thegully deposit at the foot of the Great Red Hills where the Ganggou gullies emerge onto the Guanting Basin, and the palaeo floods lack water deposits of the Yellow River in the barrier lake in the Jishixia. The results show that at ca. 3950 a BP, immediately followed by a major earthquake, the settlement was overtaken by immense mudflows coming along the tributary gullies from the hillsides behind. The enormous mudflows suddenly buried and destroyed the dwellings, which led to the prehistorical calamities in the Lajia Ruins. These results are of important implications in understanding the prehistorical environmental change in the environmentally sensitive zones over the world. It has very important reference value for the further studying of man-land relationship.

Keywords: *Guanting basin, Lajia Ruins, prehistorical catastrophes, earthquake, mudflow*

EXTENDED ABSTRACT ONLY

Changes in dust activities over East Asia under a global warming scenario

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Abstract: Atmospheric dust is the main aerosol component over the East Asia. The atmospheric dust over the East Asia influences climate at local and regional scales through its direct effects on solar and longwave radiation. In this study, based on the dust simulations from the Coupled Model Intercomparisons Phase 5 (CMIP5), the spatial and temporal changes in the dust aerosols over East Asia for the period of 2030s (2016-2035) and 2050s (2046-2065) under a global warming scenario of Representative Concentration Pathway 8.5 was examined. The results show that the CMIP5 models can reproduce spatial and temporal variations in East Asian dust during 1986-2005. The simulated high dust optical depth (DOD) are consistent with observed ones in East Asia. Meanwhile, a long-term decreasing trend in DOD over Taklimakan Desert is simulated by the CMIP5 models over the period of 1986-2005. By comparing historical simulations with those in 2030s and 2050s, the DOD over East Asia will decrease during 2030s and 2050s, indicating decreasing dust activities over East Asia. The decrease of dust activities in East Asia is related to decreasing intensities of the Aleutian Low over the northern Pacific Ocean, the East Asian trough in the middle troposphere, and the westerly winds in the upper troposphere. The weakening Aleutian Low and East Asian trough contribute to decreased northerly winds over East Asia in the lower troposphere and hence decrease the occurrence of dust storm over Mongolia and northern China. The decreasing westerly winds in the upper troposphere is not helpful for dust transport eastward from the Middle Asia and Mongolia to the eastern China. In addition, vegetation cover increases in 2030s and 2050s in northern China and southern Mongolia, which will prohibit dust emission and dust storm occurrence over East Asia.

Keywords: *Dust activities, CMIP5, dust optical depth, East Asia*

The impact of dynamically downscaled rainfall bias on modelled runoff response to climate change

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Abstract: The Victorian Climate and Water Initiative is supporting the development of realistic catchment scale daily rainfall projections to better inform and quantify the potential impacts of climate change on regional water supply across Victoria, Australia. Dynamically downscaled future projections of global climate model outputs can potentially provide useful and plausible higher resolution hydroclimate projections. However, there is often a need for bias correction of the simulated daily rainfall before it can be used in hydrological modelling. For WRF simulations available through NARCliM, we applied quantile-quantile mapping (QQM) to bias correct the distributions of daily rainfall on a seasonal basis for all grid points in Victoria individually. We then examined the effect of this bias correction on: (i) biases both before and after bias correction in different rainfall metrics; (ii) change signals in metrics in comparison to the bias; and (iii) the effect of bias correction on wet-wet and dry-dry transition probabilities. We demonstrate that such quantile mapping bias correction methods are unable to correct the underestimation of autocorrelation of rainfall sequencing, which suggests that new methods are needed to properly bias correct dynamical downscaling rainfall outputs.

We show that the QQM bias-corrected daily rainfall from dynamically downscaled WRF simulations of current climate produce biased hydrological simulations. While the QQM bias correction can remove bias in daily rainfall distributions at each 10 km^2 grid point across Victoria, the GR4J rainfall-runoff model underestimates runoff when driven with the QQM bias-corrected daily rainfall. We compare simulated runoff differences using bias-corrected and empirically scaled rainfall for several key water supply catchments across Victoria and discuss the implications for confidence in the magnitude of projected changes for mid-century. These results further highlight the imperative for methods that can correct for temporal and spatial biases in dynamically downscaled daily rainfall if they are to be suitable for hydrological projection.

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Potter, N. J., Chiew, F. H. S., Charles, S. P., Fu, G., Zheng, H., and Zhang, L. (2109) Bias in downscaled rainfall characteristics, Hydrol. Earth Syst. Sci. Discuss., https://doi.org/10.5194/hess-2019-139, in review.

Keywords: *Climate change, dynamical downscaling, bias correction, projections, rainfall-runoff modelling*

An evaluation of the MACA statistical downscaling approach on fire weather variables for Victoria, Australia

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Abstract: South-eastern Australia is particularly prone to wildfires, and fire weather is expected to become more severe in this region during the 21st century. There is a need to understand the changes to fire conditions that occur on the local scale to assist with planning and fire management decisions. Downscaling climatic variables relevant to fire weather will assist with these decisions. The Multivariate Adaptive Constructed Analogs (MACA) downscaling approach incorporates observed climatology to allow model-generated fields to be determined at a higher resolution. In the work described here, the MACA approach is used to downscale daily maximum temperature, minimum relative humidity, wind, and precipitation for Victoria, Australia. Downscaling is performed on a single CMIP5 model, ACCESS1-0, to produce a historical downscaled dataset for 1973-2016 at 4km resolution, and a similar dataset for the RCP8.5 scenario to 2060. We evaluate the historical downscaled data against a gridded reanalysis dataset for Victoria from 1972–2016 (VicClim) in terms of seasonal means and extreme fire danger days, as measured by the McArthur Forest Fire Danger Index (FFDI), and evaluate changes in the RCP8.5 scenario.

We find that the MACA downscaling approach reproduces monthly mean maximum temperature and humidity with a very high degree of accuracy including across complex terrain and land-sea boundaries, which are not easily considered by simple cubic interpolation (Figure 1). Extreme (99th percentile) fire danger is underestimated in the downscaled data, mainly caused by underestimates of wind speed on days of extreme fire danger, and the high sensitivity of FFDI to wind speed. Thus, extreme values need to be interpreted with care as they may be influenced by model biases to which the FFDI is highly sensitive.

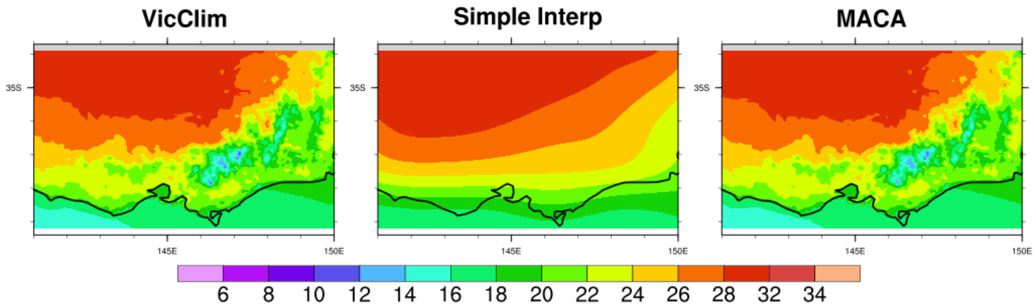

Figure 1. November-March mean maximum temperature in (left) VicClim reanalysis 1972-2016, (middle) ACCESS1-0 1972-2016 with simple cubic interpolation, (right) As for middle, but with MACA downscaling.

By mid-century under the RCP8.5 scenario, an increase in mean and extreme FFDI is expected across all of Victoria. In northern Victoria, the main driver of FFDI changes is an increase in temperature, while an increase in the drought factor used to calculate FFDI is a driver of similar magnitude over southern Victoria. An increase in relative humidity in eastern Victoria is expected to negate changes due to increased temperatures. The ability of MACA to resolve changes to this resolution highlights its potential to be used in a multi-model evaluation of future climate over regions with high-resolution observed or reanalysis data.

Keywords: *Fire weather, downscaling, south-eastern Australia, CMIP5*

Realised added value in dynamical downscaling of Australian climate change

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Abstract: Coarse resolution global climate models (GCM) cannot resolve fine-scale drivers of regional climate, which is the scale where climate adaptation decisions are made. Regional climate models (RCMs) generate high-resolution projections by dynamically downscaling GCM outputs. However, evidence of where and when downscaling provides new information about both the current climate (added value) and the projected climate change signal relative to driving data is lacking. Seasons and locations where CORDEX-Australasia ERA-Interim and GCM-driven RCMs show added value for mean and extreme precipitation and temperature are determined. We introduce a new concept, 'realised added value', that identifies where and when RCMs simultaneously add positive value in the present climate and project a different climate change signal, thus suggesting plausible improvements in future climate projections by RCMs. ERA-Interim-driven RCMs strongly add value to the simulation of summer-time mean precipitation, especially over northern and eastern Australia. GCM-driven RCMs show added value for precipitation over complex orography in southeastern Australia during winter, and widespread added value for mean and extreme minimum temperature during both seasons, especially over coastal and high-altitude areas. RCM projections of decreased winter rainfall over the Australian Alps and decreased summer rainfall over northern Australia are collocated with notable realised added value over these regions. Overall, realised added value is strongest over high elevation/complex orography, and over southwestern and northern regions, as compared to other regions in Australia. Our assessment of the varying RCM capabilities to provide realised added value to GCM projections can inform climate adaptation decision-making and model development.

Keywords: *Climate impact adaptation, CORDEX-Australasia, extremes, precipitation, regional climate modelling, temperature*

Future projections of Australian bushfire conditions: ensemble of ensembles approach for examining regional extremes

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Abstract: Projected changes in fire weather conditions throughout Australia were examined using a multi-method approach, including two ensembles of regional climate models as well as an ensemble of global climate models quantile-matched to observations-based data. Extreme wildfires have recently caused disastrous impacts in Australia and other regions of the world, including events with strong convective processes in their plumes (i.e., strong pyroconvection). The McArthur Forest Fire Danger Index (FFDI) was used to represent near-surface weather conditions and the Continuous Haines index (CH) was used here to represent lower to mid-tropospheric vertical atmospheric stability and humidity measures relevant to dangerous wildfires and pyroconvective processes. Projected changes in extreme measures of CH and FFDI were examined using this multi-method approach. The projections show a clear change over this century towards more dangerous near-surface fire weather conditions for all regions throughout Australia, due to increasing greenhouse gas emissions (Dowdy et al. 2019). The projections also show increased pyroconvection risk factors for some regions of southern Australia.

Reference: Dowdy AJ, Ye H, Pepler A, Thatcher M, Osbrough SL, Evans JP, Di Virgilio G & McCarthy N (2019) Future changes in extreme weather and pyroconvection risk factors for Australian wildfires. *Scientific Reports,* **9**, doi:10.1038/s41598-019-46362-x.

Keywords: *Wildfire, ensemble, climate change*

INVITED PAPER

EXTENDED ABSTRACT ONLY

Compound rainfall events in Tasmania

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Abstract: Atmospheric and oceanographic physical processes interact across a wide range of temporal and spatial scales. While natural disasters can be caused by a single anomalous event, such as heavy rainfall, windstorms, heatwaves, droughts and bushfires, high-impact natural disasters are often the result of a complex interaction between several events. In these situations, natural disasters may occur in either singular or separate regions, and can occur concurrently or in sequence. This combination of hazards is referred to as multi-hazard 'compound' events. Compound events that occur in a single region amplify the impact on the community, whereas independent events that occur in separate regions have increased impact due to the extra load placed on emergency response resources. Typically, risk assessment only considers one hazard and one event at a time. However, an area can be affected by a number of these hazards (or one multiple times), over a short time, putting pressure on emergency services and exacerbating the impact of the hazard. The Climate Futures team are exploring Tasmanian compound events, which are of concern to emergency services managers, energy providers and other government and industry stakeholders.

An example of when a single meteorological parameter can produce compound events at the same location is rainfall. Flooding can occur on days where the rainfall is not particularly extreme but the precipitation falls on an already saturated catchment. This is because the infiltration capacity of the soil is greatly reduced. Capturing the antecedent conditions of the catchment is vital for correctly estimating the rainfall to run-off process and in turn, flood risk.

Here we present results on how Tasmanian compound flooding events are projected to change over time using four climatologically diverse river catchments representing regional variability in climate. We highlight that flooding can also occur on relatively low rainfall days if, due to antecedent conditions, the catchments are already saturated. We introduce a number of novel statistical methods to identify these compound events and quantify the relative intensities of such events.

To assess future risk, we use simulations from the Coupled Model Intercomparison Project (CMIP5), dynamically downscaled over Tasmania using the CSIRO's Conformal Cubic Atmospheric Model. This increases the resolution from ~200km to ~10km and produces hourly timesteps. We downscaled the models from the "business as usual" emission scenario (RCP 8.5) of the IPCC Representative Concentration Pathways, using six parent global climate models, simulating from 1961 to 2100. Outputs were then bias adjusted using 'quantile' statistical transformations, which has been widely used for adjusting modelled precipitation.

To date, this analysis and assessment is the highest resolution investigation of climatological compound events over the Tasmanian domain completed within the historical or future contexts.

Keywords: *Flooding, compound events, regional climate change*

Regional Climate Modelling with WRF-LIS-CABLE: simulation skill of Australian climate and extremes

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Abstract: Regional climate models are the ideal tool for investigating regional climate and extremes at spatial scales more resolved than the typical global climate model. The Weather Research and Forecasting (WRF) model is widely used by the regional climate modelling community and has the advantage of allowing the user to configure different physical parameterisations to create physics ensembles. However, a limitation of this approach is that there is limited guidance on which configurations are fit for purpose, particularly on whether the same configuration can be used to study extreme events and climate means. Therefore, the aim of this study is to provide guidance on the configurations of an enhanced version of WRF that perform reasonably well at simulating both Australian climate and extremes.

In this study, we use an enhanced version of WRF developed by NASA with the Land Information System (LIS) to couple the Community Atmosphere Biosphere Land Exchange (CABLE) land surface model. We call this model system WRF-LIS-CABLE. WRF-LIS-CABLE has the advantage that CABLE can be run offline to spinup all land surface state variables more efficiently and therefore avoid long spin-up times required for coupled simulations. We create a WRF physics ensemble that includes 3 radiation schemes, 3 planetary boundary layer schemes and 4 cumulus parameterisations, providing an ensemble of 36 unique atmospheric configurations. Simulations are run for a domain covering Australia, New Zealand and Indonesia for the period October 2008 to October 2010. This period covers the transition out of the Millennium Drought where a number of extremes events were experienced.

Our results indicate that simulation skill is generally lower over tropical Australia and Southwest Western Australia compared to South East Australia. This is associated with a systematic dry bias, particularly during the monsoon season over tropical Australia that contributes a hot temperature bias. Limitations in the representation of savanna ecosystems, the initialisation protocol and the domain resolution were identified as the main reasons behind the systematic biases. Resolving this bias is the focus of future research. A single best-performing model configuration of WRF-LIS-CABLE for all regions, variables or weather phenomena does not exist. However, we are able to provide recommendations on configurations for particular purposes regarding region of interest within Australia and whether the focus is on climate means, extremes or both.

Keywords: *Physics ensemble, climate extremes, CORDEX AustralAsia*

Impact of bias corrected WRF lateral boundary conditions on extreme rainfall events

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Abstract: The accurate description of changes in extreme rainfall events requires high resolution modeling. However, the applicability of global climate models (GCMs) is limited by the fact that the spatial and temporal resolution are insufficient to provide output at the right scales for assessing changes in extreme rainfall. Regional climate models (RCMs), where GCM data are used to provide boundary conditions, are a widely used method to resolve finer resolution. A problem with this, however, is their application is hindered by systematic biases contained in input boundary conditions which can be propagated into RCM outputs. To deal with these considerable biases, many bias correction methods ranging from simple scaling to complexed techniques have been applied to the input boundary conditions.

In this study we focus on the impact of bias corrections on the lateral boundary conditions (LBCs) on extreme rainfall events. Three bias correction methods are used: mean, mean and variance, and nested bias correction (NBC) which includes corrections for lag-1 autocorrelations. The corrections are applied to 6-hourly atmospheric and surface variables taken from the GCM dataset to drive a regional climate model, resulting in 12 correction factors for a monthly correction. The bias correction methods are applied over a 31-year model run with the first year negated to remove spin-up effects. The GCM used here is the Commonwealth Scientific and Industrial Research Organization's Mk3.5 (CSIRO), and Weather Research and Forecasting model (WRF) is the RCM used in this study. European Center for Medium-Range Weather Forecast's (ECMWF) ERA-Interim (ERA-I) reanalysis model is used as an "observational" reference for bias correction. The downscaling is performed over the Australasian Coordinated Regional Climate Downscaling Experiment (CORDEX) domain and the performance of bias correction is assessed over the Australian landmass.

To evaluate the impact of bias correction on the WRF output, root-mean-square errors (RMSE), correlation coefficient (R), and bias are used. To evaluate the performance of bias correction on extreme rainfall indices from World Meteorological Organization (WMO) Expert Team on Climate Risk and Sectoral Climate Indicators (ET-CRSCI) are used. Then, the results are evaluated comparing corrected WRF and ERA-I-driven WRF.

It is clear from the statistics used here that bias correction on the LBCs produces a considerable improvement in daily precipitation percentile indices. The results also show that most of the improvements are gained from a correction in the mean field, and it substantially reduces the extreme precipitation variability.

Keywords: *Regional climate model, boundary conditions, bias correction, extreme rainfall events*

Evaluating hydrologic stress under climate change

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Abstract: A considerable body of research has been published on the projected hydrological changes associated with a warming climate. Within such studies, the impacts of climate change on hydrology are commonly characterised as changes in the long-term behaviour of selected components of the water cycle. Assessing impacts in terms of changes in the statistics of long-term behaviour is readily presented and understood, but such measures are not well suited to assessing the *significance* of the impacts in a manner that accommodates expected differences due to climatology, physical attributes, and system-specific characteristics. Furthermore, the temporal resolution of most long-term studies is not sufficient to capture the impact of variability over shorter periods to which the life histories of environmental systems are often intimately linked. Without understanding how the variability of system inputs impact on the outputs, it is difficult to assess whether a given change in a performance metric is of concern or not.

In this paper we develop an approach that facilitates comparison of hydrologic performance of different systems under current and future projected climate conditions. The approach is relevant to the assessment of hydrologic systems that vary in response to climatic variations in temperature, rainfall, and evaporation over various time scales. Such systems include services based on freshwater resources, terrestrial and freshwater ecosystems, coastal and marine systems, and food security and production systems. The proposed measure of stress is intended to facilitate ready comparison across different sites to identify those most at risk and consists of four major steps (see Fig 1) involving 1) the identification of a period that is characteristic of system stress, 2) the derivation of an ensemble of hydroclimatic sequences representative of current and future conditions, 3) the simulation of system performance for each member of the ensemble, and 4) the evaluation of hydrological stress through comparison of the distribution of performance metrics.

An important element of the approach is that behaviour is evaluated over a time period that is characteristic to the performance of the system. This "characteristic period" may be short or long compared to the period of available record. If short, then a range of behaviour can be assessed by evaluating performance metrics over samples selected from the entire time series; if long, then it will be necessary to employ stochastic procedures to generate multiple replicates that preserve the same statistical properties of the original time series. These series are perturbed to reflect the impacts of climate change, and the degree of stress is evaluated with reference to the difference performance metrics obtained from the analysis of both time series.

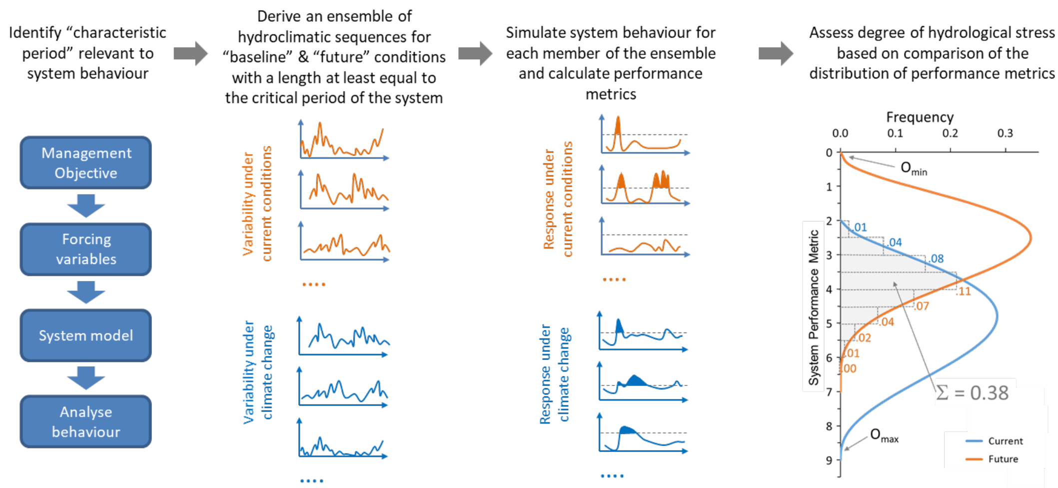

Figure 1. Approach used to calculate the stress metric resulting from a projected level of climate change

Keywords: *Integrated modelling, integrated assessment frameworks, conceptual model*

EXTENDED ABSTRACT ONLY

Changing patterns of snowpack due to climate change

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Abstract: Snowpack provides a natural storage of water as well as the primary source of stream flow and water supply in the many parts of the world. However, increasing greenhouse gas (GHG) concentration is leading to intensive change of climate such as global warming which in turn is affecting hydrological processes, including snowpack. To explore change of snowpack in accumulation and depletion periods across Northern hemisphere, this research is twofold. In the first part, the trends in snow accumulation and depletion were inspected by means of global snow water equivalent datasets (SWE) against time and air temperature during 1980 to 2014. This includes data sparse regions and remote areas where effect of global warming in the change of snowpack is not well understood to date. We found that large areas show decreasing accumulation rates and increasing depletion rates over time. Our results show the same pattern of change when investigated concerning temperature too. In addition, snowpack change is following similar pattern in USA and Tibet which could be results of ongoing observed poleward expansion of the Hadley cell in the Northern Hemisphere. Then, we assess change of snowpack in future projecting GCMs (global climate models) and RCMs (regional climate models) simulation using RCP8.5 (Representative Concentration Pathway) scenario in Tibetan plateau, where water melt from snowpack provides water flow to the major Asian rivers and the large population which depends on water from these rivers. However, GCMs and RCMs simulation have bias which will affect the estimation of snowpack change in catchment scale. We used multivariate recursive nested bias correction (MRNBC) approach to correct systematic bias of climate modelled temperature, precipitation and SWE jointly instead of separate bias correction to preserve the dynamic relationships among the climate variables. MRNBC procedure reduced bias of GCMs and RCMs significantly. Our results show that annual SWE is decreasing in both near future (2041 to 2064) and far future (2071 to 2094) with respect to historical periods. Possible reasons for this change are warming temperature, varying precipitation i.e. more rainfall than snowfall, and change of humidity which affects snowmelt process. This change will affect runoff, water supply and ecosystem in this region.

Keywords: *SWE, warming temperature, GCMs, RCMs, climate change, future projection*

Downscaled projections of hydrological variables for Australia

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Abstract: Climate change is likely to have major impacts on many human and natural systems. For instance, changes in the hydrological cycle induced by climate change may have dramatic impacts on flood risks and changes in water availability and quality. Planning for the effects of climate change on water resources is critical, particularly in regions such as Australia which exhibit large natural variability such that climate change may enhance the deleterious effects of intermittent water supply. In Australia the influence of climate change on rainfall has already been observed via declining rainfall in southwest Western Australia and southeast Australia (e.g. Hope et al., 2009) and projections indicate that this will continue into the future (CSIRO and Bureau of Meteorology, 2015).

The Global Climate Models (GCMs) used in the most recent CMIP5 have grid cell sizes of the order of 150 km, which is too large to extract meaningful information about the impacts of climate change on catchment scales (of the order of 10s of kms). To provide meaningful information at such scales requires bias correction of the GCM data to observations and further disaggregation of the GCM data to the scale of the observations. Much of the effort in regional downscaling in Australia has been applied at the State level and often with differing methodologies, whether they be statistical or dynamical methods. The Australian Bureau of Meteorology is addressing this disparity in Australian downscaled projections by developing a National Hydrological Projections Service to provide the community with estimates of climate change on future Australian water resources.

Currently, the model chain consists of: (1) four GCMs, (2) three statistical bias correction methods, (3) two spatial disaggregation techniques and (4) one hydrological model. This presentation provides an overview of the selection of GCMs, the bias correction methods and the spatial disaggregation techniques used to produce the downscaled input to the Australian Bureau of Meteorology's hydrological model (AWRA-L). The input variables are precipitation, solar radiation, minimum and maximum near-surface air temperature and surface winds.

In this presentation we focus on the biases present in the GCMs compared to gridded observations (AWAP), the climate change signal of the hydrological variables projected by the GCMs and the impact of the bias correction and spatial disaggregation methodologies on their climate change signal. Furthermore, we compare the statistical downscaling methods with the dynamically downscaled output from the CSIRO Conformal Cubic Atmospheric Model (CCAM).

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Keywords: *Hydrological projections, bias correction, downscaling*

Climate data for next generation projections in southeastern Australia

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Abstract: Water supply and demand planning in Victoria is currently informed by climate and runoff projections and guidelines developed by DELWP and the Victorian Climate Initiative. The next generation projections will be developed from hydrological modelling informed by future climate projections from CMIP6 GCMs and readily available and bias-corrected downscaled data. Climate change information can be obtained from a range of models and methods, including raw GCM data, bias corrected data, and statistically and/or dynamically downscaled climate information. Due to the large computational requirements and long development time of dynamically downscaling products, use of these for hydroclimate projections is frequently opportunistic, the most recent products available for south-eastern Australia are NARCliM 1.5 (Downes et al., 2019) and CCAM (Rafter et al., 2019).

A major challenge in developing hydroclimate projections is reconciling and combining different climate data sources. Bias correction and downscaling can change trends and other features of climate data. In this paper we present an overview of current data availability for next generation projections, comparing latest products to each other as well as previously used climate data (CMIP5 models). We conclude with preliminary recommendations for combining and using climate data to develop an optimal framework for developing next generation projections for southeastern Australia, as well as suggestions for further research.

Downes, S., Beyer, K., Ji, F., Evans, J., Di Virgilio, G., and Herold, N. The next generations of NSW/ACT Regional Climate Modelling (NARCliM). AMOS-ICTMO 2019, 11–14 June 2019, #102, Darwin, Australia, 2019.

Rafter, T., Trenham, C., Thatcher, M., Remenyi, T., Wilson, L., Heady, C., and Love, P. (2019) CCAM Climate Downscaling Data for Victoria 2019 http://hdl.handle.net/102.100.100/77939?index=1

Keywords: *Next generation projections, climate change, dynamical downscaling, bias correction*

EXTENDED ABSTRACT ONLY

Ocean wave climate modelling at global and regional scales

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Abstract: Ocean waves play a key role in ocean surface dynamics, particularly in defining coastal dynamics and natural hazards. Understanding current and future wave climate is vital for coastal and off-shore infrastructure planners, as well as for researchers and policy makers in understanding possible climate change impacts from sea level rise combined with changes in waves and other ocean and atmospheric processes. The Sea Level, Waves, and Coastal Extremes team within CSIRO's Climate Science Centre has created several modelled ocean wave data products over recent years using different forcings (reanalyses, global and regional climate models); facilitating improved scientific understanding of ocean wave processes in these areas.

The CAWCR Wave Hindcast provides a reference wave data product both globally, and regionally around Australia and the Western Pacific at higher resolutions. This dataset was created as a collaboration between CSIRO and the Australian Bureau of Meteorology using the WaveWatchIII model, and is maintained on a monthly basis from 1979 to present. Wave variables are available on five regular grids, as well as directional wave spectra at over 3600 points. The dataset contains hourly wave model data, forced with Climate Forecast System Reanalysis (CFSR) surface winds and sea-ice. It is one of the CSIRO Data Access Portal's most accessed data collections. Applications of the hindcast include global and regional wave climate investigations; assessment of ocean wave energy resources (e.g. the Australian Wave Energy Atlas); assessing the contribution of storm waves to coastal extremes, such storm tides and episodic coastal erosion events; and providing boundary conditions for use with high-resolution regional or local-scale wave and littoral (coastal process) models.

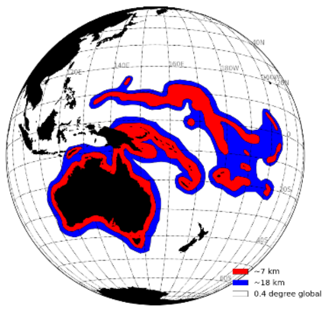

Figure 1. Wave hindcast grids

To estimate projected global and regional changes in wave climate, CSIRO researchers investigated wave projections using an 8-member ensemble of CMIP5 global climate models (GCMs). Surface winds (3-hourly) and sea-ice projections from the GCMs were used to force the WaveWatchIII model on a 1-degree global grid in historical and two projection scenarios (RCP4.5 and RCP8.5). Researchers around the world have used different modelling approaches with CMIP5 data to produce wave climate projections. This provided the opportunity to assess the uncertainty in projections not just between GCMs in a given wave modelling approach, but across different methods and implementations, both dynamical and statistical. The Coordinated Ocean Wave Climate Project (COWCLIP) facilitated standardisation and collation of the various global wave climate projections, enabling an analysis of the variation and uncertainty of wave climate projections. The key finding of this work is that despite increased uncertainty in wave projections arising from differences in the contributing modelling approaches, robust changes in wave height, period and direction are projected under the high emissions RCP8.5 scenario by the end of the 21st Century.

Regional climate data can also be used to force finer scale wave models. CSIRO's Conformal Cubic Atmospheric Model (CCAM) is used to downscale global GCM data to 5 km resolution in target regions, facilitating wave and coastal modelling studies at much higher spatial resolution than the GCMs. The Sea Level, Waves, and Coastal Extremes team is undertaking a detailed coastal hazards assessment of Port Phillip Bay in Victoria using reanalysis data and GCM data as CCAM forcing to downscale to the region of interest. This downscaled atmospheric data will be used to drive an unstructured mesh coastal process model including waves, to understand possible future changes to the coastal environment in Port Phillip Bay.

Keywords: *Waves, wave modelling, hindcast, projections, coastal modelling, coastal extremes*

EXTENDED ABSTRACT ONLY

Impacts of natural variability and climate change on tourism related snow indices

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Abstract: Winter tourism is one of the most vulnerable economic sectors to climate change, but also natural climatic variability is significantly impacting revenues of winter sports providers. Numerous studies have investigated the impact of climate change on winter tourism. Nevertheless, those studies have almost exclusively focused on changes in the mean state of the climate. While multiple studies mention the importance of natural climatic variability for snow depth and winter tourism, no study quantifies the impacts of both, natural climatic variability and climate change, on the winter tourism industry. This is in parts due to the relatively large uncertainties in regional climate modelling and associated impact studies. When applying regional climate model (RCM) ensembles, e.g. from the CORDEX initiative, it remains difficult to distinguish between model uncertainties and uncertainties arising due to natural climatic variability. When regional climate models are applied in impact studies, natural climatic variability is among the biggest contributors to overall uncertainty, especially on shorter timescales and for regional applications. To overcome this research gap, we apply a single model large ensemble, which makes it possible to quantify the uncertainties associated with natural climatic variability.

In this study, we use the 50-member single regional climate model large ensemble (CRCM5-LE) from the ClimEx-project (www.climex-project.org) to analyze the impacts of natural variability and climate change on snow indices at multiple locations in Switzerland. Each ensemble member undergoes the same external forcing (RCP8.5), but slightly different atmospheric initial conditions. Therefore, the difference between the 50 members arises due to natural climatic variability and the 50 realizations are all equally likely outcomes of climate change over the next century. We use a quantile mapping approach to bias correct and downscale the RCM from the 12 km grid to the station scale to drive the physically-based snow model SNOWPACK to model snow depth and snow water equivalent.

Based on the results we derive tourism related snow indices, such as the number of days with closed snow cover, the number of days with sufficient snow depth for winter sports activities and the number of days suitable for artificial snow-making.

Our approach allows a probabilistic assessment of natural climatic variability under a given emission scenario and its impact on tourism-related snow indices. Our results are of interest to hydrologists, touristic regions and winter sports providers.

Keywords: *Regional climate models, natural variability, large ensemble, impact modelling, snow modelling*

Evaluation of precipitation from a regional reanalysis for Australia and its applications

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Abstract: Precipitation is a fundamental input for the modelling of natural processes, hydro-meteorological analysis and forecasting. However, accurate precipitation datasets that provide sub-daily representations of spatio-temporal variability are generally not available due to scarce gauge measurements and limited high-resolution datasets. Global and regional reanalysis datasets provide an alternative source of precipitation data at consistent spatial and temporal resolution. The regional reanalysis, in particular, improves upon global reanalysis by making use of local observations and a regional model-based data assimilation. BARRA-R (The Bureau of Meteorology Atmospheric high-resolution Regional Reanalysis for Australia) is the only regional reanalysis for Australia. As this is a novel dataset, it is deemed essential to evaluate this dataset to ascertain its efficacy for further hydrometeorological applications.

An extensive evaluation of the BARRA-R precipitation is performed at various temporal and spatial scales using a range of existing and adapted metrics to ascertain the overall value of the product. We compare BARRA-R precipitation against various sources of datasets: (sub-)daily gauge measurements, Australian Water Availability project (AWAP), ERA-Interim, and a blended radar product.

Overall, BARRA shows an improved representation of precipitation over ERA-Interim displaying a fine-scale spatial and temporal variability. However, the performance is dependent on spatial location with superior performance at temperate than tropical and arid zones (Figure 1). The general precipitation statistics are closely reproduced by BARRA-R, with increasing performance when temporally aggregated. In addition, our analysis at both point and spatial scale suggests a potential spatial displacement of precipitation fields during large rainfall events.

Following the evaluation, we explore the potential of sub-daily rainfall information from BARRA-R in engineering design and hydrological modelling. A summary of these evaluations will be presented and implications of these findings on the potential use of BARRA-R precipitation will be discussed.

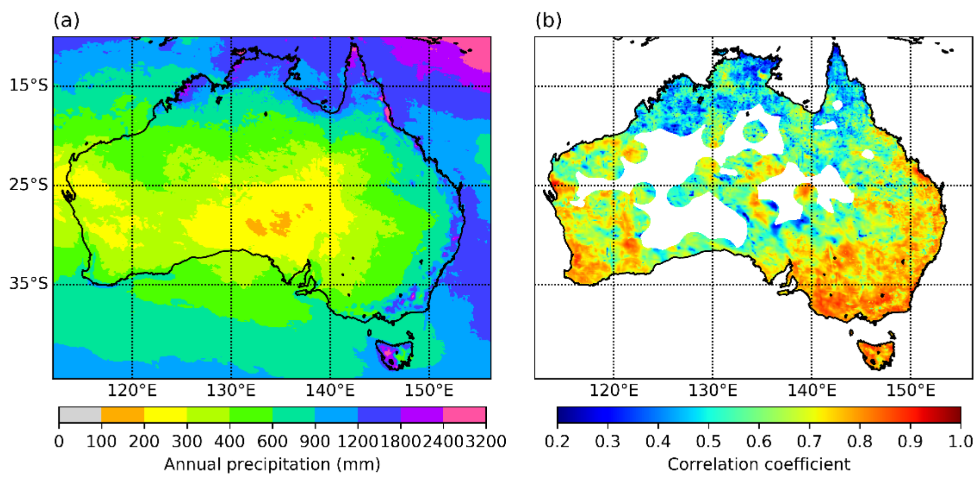

Figure 1. (a) Average annual precipitation from BARRA, (b) Correlation coefficient for BARRA precipitation against AWAP dataset. Missing values and ocean are masked in correlation plot.

Keywords: *BARRA-R, regional reanalysis, rainfall evaluation*

EXTENDED ABSTRACT ONLY

Evaluation of GPM IMERG rainfall estimates under different rain gauge densities in the high elevation tropical Andes

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Abstract: Satellite-based estimates of rainfall are now frequently being used to complement scarce networks of gauges, particularly in remote and inaccessible areas such as mountainous regions. Understanding the associated uncertainties is important before the data are applied, but understanding is often limited due to low density of ground gauges and associated scale-related errors. This is of particular importance in mountain regions, which are characterised by complex topography and highly variable rainfall patterns over short spatial scales that are generally smaller than the resolution of the satellite products.

This paper utilises a unique dataset containing 15 rain gauges at elevations ranging from 3,800 to 4,600 m above sea level to evaluate the Integrated Multi-satellite Retrievals for Global Precipitation Measurement mission, more commonly referred to as IMERG, performance in the tropical Andes of Peru. Even though numerous satellite precipitation products exist, IMERG is of particular interest for mountainous regions due to its fine spatiotemporal resolution (30 minutes and 0.1°), increased sensitivity to light rain and snow detection, and suitability to a wide array of applications because of both "Near Real Time" and "Research" level product availability. The 15 gauges represent one IMERG grid so provide a rare evaluation opportunity in this geographical context.

IMERG performance was evaluated from two main perspectives. First, both IMERG "Near Real Time" and "Research" products are evaluated at the native resolution (30 minutes) using a combination of performance metrics, including estimation bias indices, categorical indices, and an error decomposition approach. Error dependencies on rainfall characteristics and source instrument / processing algorithm are also investigated. Second, the impact of gauge density on perceived 'performance' is examined at different temporal scales (ranging from 30 minutes to 24 hours) by evaluating different gauge combinations.

Our findings show that IMERG performance is limited at the 30-minute resolution predominantly due to significant under-detection of events, while Near Real Time products have better skill at rainfall intensity estimation than the research level product which tends to overestimate intensities. Performance is strongly influenced by rainfall intensity and variability, and also by the source instrument, with infrared-based estimates surprisingly having better detection skill than those derived from passive microwave. We conclude by highlighting the influence of gauge density on perceived 'accuracy' (Figure 1) and provide recommendations on how this problem might be accounted for by IMERG end users.

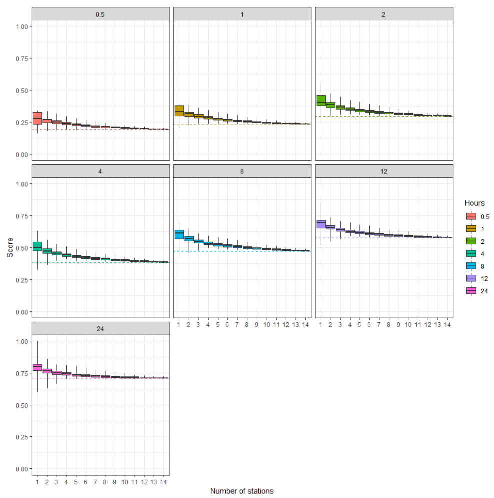

Figure 1. Boxplots of probability of detection scores for different gauge combinations from 30 minutes to 24 hours.

Keywords: *IMERG, precipitation, high mountains, uncertainty*

Daily rainfall data infilling with a stochastic model

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Abstract: Most models are premised on complete data without missing values, such as using a complete daily weather time series to simulate crop biomass accumulation and production, and predict pest risk, even assess climate change impacts. However, historical data series often have some missing values or have only the aggregated values over a period of time. For example, daily rainfall amount is normally recorded by hand during working days and the data during weekends and holidays are sometimes missing and reported as total during these periods. In addition, some data are still missing even nowadays with automated weather stations, due to instrument failure, power outages, operation interruption and so on. Daily rainfall time series data may suffer from several missing data problems. These include (1) individual missing days, (2) consecutive missing days (missing segments), (3) consecutive missing days with their aggregation available. Aggregation of daily data is most common following weekends or holidays. There are several methods to infill these missing values, such as distributed accumulated rainfall evenly over the accumulation period, spatial interpolation from records of surrounding stations, and climatology. These methods often under-estimate the dry day proportions, i.e., giving more wet days than normal, and smooth out extremely daily rainfall amount.

To infill these data gaps appropriately, we investigate a time-varying stochastic model to simulate daily rainfall time series based on true observations, including aggregated observations. A complete rainfall time series is constructed using a three-state Markov chain model to simulate the occurrence of dry, wet and extremely wet days, whilst rainfall amounts for wet and extremely wet days are modelled using a truncated Gamma distribution and an extended Burr XII distribution respectively. Smooth changes on state transition probabilities within a year are captured by time-varying model inputs. The proposed technique can infill the missing data with or without aggregated observations. Experiments on three Australian stations from different climatic zones illustrate its superior performance to a defacto operational approach in Australia and classic climatology method in terms of maintaining daily rainfall data characteristics such as dry day proportions, dry day spells, and rainfall amount distributions. For example, average dry day proportions for these three stations are around 80% based on truly daily rainfall records. They are around 50% for the daily data infilled by our proposed stochastic method. Because these missing daily data do not have substantially missing patterns, these proportions are more reasonable than around 20% for the infilled daily data from the defacto operational approach.

Keywords: *Markov Chain, extremes, temporal disaggregation, missing data*

Improved precipitation estimates using neural networks to merge radar and geostationary satellite images

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Abstract: Surface precipitation can be measured with a variety of sensors, such as rain gauges, radar and satellite remote sensing. No single source accurately represents the observed precipitation over large geographical areas. Merging information from different observation sources has the potential to overcome the limitations of individual methods. In this work, we present a methodology for combining rain estimates from radar and geostationary satellite imagery. Meteorological radar networks provide accurate measurements of the precipitation occurring around the station, with good temporal and spatial resolutions. However, radars have limited geographic coverage, and their accuracy is reduced by occlusions from surrounding terrain as well as signal echoes. Geostationary satellites provide a constant stream of images covering a large portion of our planet, but cloud-top temperature based retrievals form these data are known to be often inaccurate.

We present a methodology for combining precipitation radar data and geostationary satellite imagery using neural networks. Using Himawari-8 spectral data, we train a neural network model to learn a pixel-to-pixel relationship with Rainfields, a gauge-calibrated radar product generated by the Australian Bureau of Meteorology (BoM). The resulting trained model is capable of inferring precipitation using a combination of spectral bands from Himawari-8 as its only input. This model can be applied to new Himawari-8 images to generate a seamless precipitation estimate over its entire spatial coverage, overcoming the constraints associated with radar data.

We discuss the architecture of the proposed neural network model, as well as the methodology used to train it on the Rainfields and Himawari-8 products. We carried out experiments to assess the accuracy of models using different methodologies and independent precipitation rain gauge estimates. Results demonstrate that geostationary satellite information can complement existing precipitation measurements to provide an accurate, reliable and seamless product over large geographical areas.

Keywords: *Precipitation, weather forecasting, neural networks, weather radar, satellite remote sensing*

Economic costs of projected loss of soil organic carbon with climate change over New South Wales

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Abstract: The storage of soil organic carbon (SOC) in soils is an important element of the global carbon cycle. It influences levels of carbon dioxide and other greenhouse gases in the atmosphere, which contribute to global climate change. This study attempted to apply an economic value (in dollars) to the change in SOC attributable to climate change over NSW over the coming decades to approximately 2070.

Twelve climate models from the NARCliM program were applied to derive climate change projections. A digital soil mapping and modelling approach was adopted, involving multiple linear regression with a suite of environmental variables. Results were presented in Gray and Bishop (2019). The modelled changes in SOC stock varied between the 12 different climate projections. Results indicated average declines in SOC stocks of 3.9 t/ha (to 1 m depth) over the approx. 2000 to 2070 change period. The highest losses were revealed in the cool moist highland regions of eastern NSW, where rates of over 20 t/ha were projected.

A simple economic appraisal for SOC loss was conducted. Two approaches were used, the first using the social cost of carbon (SCC) (Nordhaus 2014) to estimate the full impact costs of this carbon loss, and the second using market prices to estimate the financial costs. Market prices were taken from Australian Carbon Credit Units (ACCUs) and the European Union Emissions Trading System (EU ETS) permits using spot prices from June 2019. These represent the dollar value for the equivalent of 1 tonne of CO_2 that is prevented from entering the atmosphere. SCC costs are from the US EPA. All prices were converted into USD using current exchange rates.

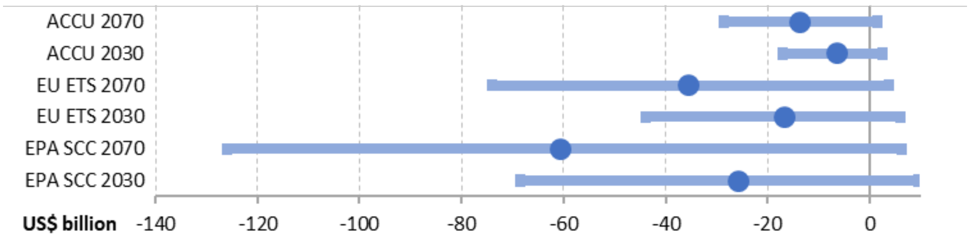

Figure 1. Value of carbon lost from NSW soils (top 1 m) due to projected climate change; SCC and market prices

Using the SCC, the mean estimate for the potential total costs over NSW is minus US\$26 billion (-\$68b to +\$10b) in 2030, growing to \$61 billion (-\$126b to +\$6b) in 2070. This cost reflects the potential global impacts of carbon emissions from NSW SOC loss. Estimates of financial costs are lower, as these reflect only the market price of avoided emissions and not the impact of those emissions (Newell *et al.* 2014). Using the EU ETS, we estimate the costs of SOC loss in NSW to be minus US\$17 billion (-\$44b to +\$6b) in 2030, growing to minus \$36 billion (-\$74b to +\$4b) in 2070. ACCU prices give lower estimates, with losses of minus US\$6 billion (-\$17b to +\$2b) in 2030 and minus \$14 billion (-\$29b to +\$1b) in 2070. These estimates, using simple economic tools, can help to raise awareness amongst decision makers on the potential impact of the climate change driven loss of SOC and these dollar values are likely to have more meaning and influence than the carbon tonnage figures alone. The results provide information for NSW land managers to assist in implementing land management practices that foster enhanced SOC storage.

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Keywords: *Soil carbon, climate change, digital soil mapping, economic costs*

Climate change and soil security: A soil erosion modelling story

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Abstract: Soil protection is critical for sustained food production and environmental services. However, soil erosion is a major cause of land degradation globally. Erosion is also expected to increase in frequency and severity due to climate change related extreme weather conditions such as floods, intense precipitation event, droughts and wildfires. Erosion processes by wind and water have been well described, and governments extensively use models predicting the extent of soil erosion for policy development.

Recent technological advances in remote sensing and Geographic Information System (GIS) have been crucial to improve the policy relevance of erosion models. Particularly, the improvement of spatial and temporal resolution of inputs has allowed models to describe soil loss better. Nonetheless, climate change is predicted to have adverse effects on soil conditions leading to an increase in soil exposure. This impact on wind and water erosion is generally treated separately, but both wind- and water-borne processes will influence future erosion dynamics and rates.

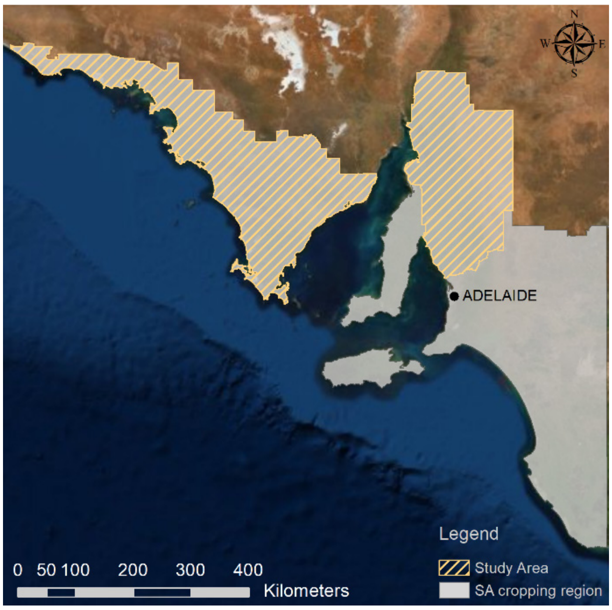

Figure 1. Presentation of the study area within the South Australian cropping region.

This paper addresses the potential to assess the broad-scale effect of climate change on soil erosion by wind and water simultaneously. Here, we describe two of the latest erosion models available and present their spatio-temporal parameterisation for Australian conditions. We used these models and NARCliM climate model projections to examine the impact of climate change on future soil loss rates and the relative balance of wind-to-water erosion over time. To model the impact of climate change we used the daily wind speed, precipitation accumulation and soil moisture datasets provided in the NARCliM archive.

Our modelled results will enable the identification of areas most at risk of erosion with a variable climate. These outputs will form the foundation for future best land management practices with extreme events and climate change. Decision-makers will then be able to identify potential for improvements, including setting priorities for investment and actions to contribute towards improving soil security for Australia.

Keywords: *Climate change, erosion modelling, soil erosion, soil security*

Controls of rainfall patterns on soil organic carbon and nitrogen stocks in Australian grasslands

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Abstract: Australia is particularly susceptible to rainfall extremes, which range from heavy monsoon rains to long droughts. In a warmer climate, regional and global climate models have projected Australia to experience an increase in the intensification of rainfall extremes at a rate of more than 10% change per ˚C temperature increase in the coming decades. Rainfall extremes can alter soil water content that drives various biogeochemical processes important for maintaining soil health and ecosystem services. In this study, we use a carbon and nitrogen cycles coupled mechanistic model (BAMS2) to investigate how the projected rainfall patterns affect soil organic carbon and nitrogen stocks in Australian grasslands located in different climatic regions.

The BAMS2 model (Tang et al., 2019) considers the depolymerization and mineralization of 11 soil organic matter (SOM) pools (i.e., lignin, cellulose, hemicellulose, peptidoglycans, monosaccharides, amino acids, amino sugars, organic acids, lipids, nucleotides, and phenols) and the transformation of inorganic nitrogen through fixation, nitrification, and denitrification. We explicitly model the growth, mortality, necromass decomposition, and water stress response of five microbial functional groups that mediate the carbon and nitrogen cycles. We include a simplified plant dynamics model to describe plant nutrient uptake, SOM inputs through root exudations and aboveground litter, and plant response to water stress. The BAMS2 reaction network is solved using a general-purpose multi-phase and multi-component bio-reactive transport simulator (BRTSim-v3.1a). In this study, the water flow along a vertical soil column is described using the Richards equation and the Brooks-Corey model for the water saturation-tension-permeability relationships, while the transport of dissolved chemicals is modeled using Darcy's advection velocity and Fick's diffusion. BRTSim-v3.1a describes aqueous complexation and gas dissolution using the mass action law, and SOM protection to soil is modeled using Langmuir's kinetics.

Our multi-decadal simulations using BAMS2 model suggest a decrease in soil organic carbon and nitrogen stocks with decreasing annual rainfall amount in all grasslands. In tropical grasslands, a 20% decrease in annual rainfall results in approximately a 10% decrease in soil organic carbon stock and less than 1% decrease in soil organic nitrogen stock. In contrast, semi-arid grasslands show a lower decrease in soil organic carbon (less than 5%), but a higher decrease in soil organic nitrogen (approximately 8%) when subject to drier conditions. With unchanged annual rainfall amount, low frequency and high magnitude rainfall events slightly increase the SOM stock in semi-arid grasslands but decrease its C:N ratio. Less frequent and more intense events in the semi-arid grasslands lead to increased soil moisture at greater depths where evapotranspiration rates are lower, hence reducing water loss to atmosphere and allowing the storage of water for plant growth. Our results show that changes in rainfall regimes alter both the total amount and stoichiometry of SOM. This study provides a modeling framework suitable for investigating SOM dynamics under various climatic and anthropogenic forcing.

Acknowledgement: *This work is supported by SREI2020 EnviroSphere program, the University of Sydney.*

Reference:

Tang, F. H.M., Riley, W. J., & Maggi, F. (2019). Hourly and daily rainfall intensification causes opposing effects on C and N emissions, storage, and leaching in dry and wet grasslands. Biogeochemistry, 1-18, https://doi.org/10.1007/s10533-019-00580-7.

Keywords: *Soil organic matter, precipitation, modelling*

Effects of snowmelt on hillslope erosion in Australian Alpine Region

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Abstract: The Australian Alpine region is highly vulnerable to extreme climate events such as heavy rainfall and snow falls, and these events subsequently impact rainfall erosivity and hillslope erosion in the region. In this study, we examined the effects of snowmelt on hillslope erosion across the Alpine region in New South Wales (NSW) and the Australian Capital Territory (ACT). We estimated rainfall erosivity, hillslope erosion and their changes in the future periods using the revised universal soil loss equation (RUSLE) and the NSW/ACT Regional Climate Modeling (NARCliM) projections with 12 model ensembles from four global climate models and three regional climate models. In this study, we used the NARCliM projected daily rainfall and snowmelt for the baseline (1990-2009), near future (2020-2039) and far future (2060-2079) periods for the Alpine region.

Adding the snowmelt as additional rainfall to the daily rainfall erosivity model resulted in greater variation in rainfall erosivity estimates in the Alpine region, especially in Springs (i.e. October). To examine the snowmelt impact, rainfall erosivity estimation adjusted by snowmelt and rainfall from the 12 NARCliM ensembles were compared with those calculated from the NARCliM rainfall projections without snowmelt. Figure 1 shows the changes of annual and seasonal mean values of rainfall erosivity calculated with and without the snowmelt component for the baseline and two future periods across the Alpine region. The snowmelt in Spring can increase the erosivity by about 12-19% in the Alpine region. However, with the projected temperature rise and snow cover decreasing, the snowmelt impact on erosivity and erosion can be ignored in the far future. On an annual basis, the snowmelt impact on mean annual rainfall erosivity is not obvious, and the change is less than 3% in the baseline and near future periods, and nil impact in the far future. As snowmelt mostly occurs in Spring, it has negligible impact on rainfall erosivity in other seasons. Overall, hillslope erosion in NSW/ACT Alpine region are predicted higher compared to the surrounding regions including Murray Murrumbidgee (MM), South East and Tablelands (SET) and Australian Capital Territory (ACT) (Figure 1). The hillslope erosion rates are predicted to increase 9 to 18% in the near and far future even assuming the groundcover is maintained at the current level. However, the groundcover is more likely to decrease as there will be less rainfall and higher evapotranspiration in the future.

This research was the first attempt to use snow data and projections to adjust erosivity model and the cover factor in hillslope erosion modelling. The methodology has been developed and applied in the NSW and ACT Alpine region, with potential to be used elsewhere in the world.

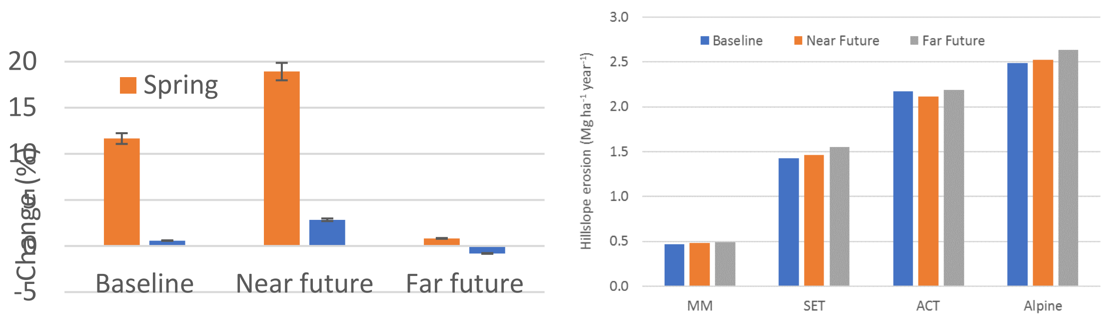

Figure 1. Predicted changes (%) of rainfall erosivity with and without snowmelt (left) in Spring, and the mean hillslope erosion rates in baseline, near future and far future periods in the Alpine and surrounding regions in NSW (right).

Keywords: *Extreme rainfall, snowmelt, erosivity, soil erosion, Alpine*

Modelling organic carbon stocks in croplands of China: the past and the future

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Abstract: Recent spatiotemporal soil organic carbon (SOC) changes in croplands of China were estimated by using a modified and validated Agro-C model. Estimates revealed that SOC in approximately 81% of China's croplands increased from 1980 to 2009. Overall, we estimated that China's croplands covering an area of 130 million hectare sequestered 730 (329 to 1095) Tg C in the topsoil to 30 cm depth, during this period. Approximately 73% of the SOC sequestration occurred in east, central and south China. The carbon sequestration was attributed to the improvement of crop production and the decrease in the removal of crop residues. Soils rich in organic carbon that received relatively low carbon inputs during the same period, however, suffered net carbon losses in Heilongjiang Province.

Meanwhile, we also used the Agro-C model to simulate climate and agricultural management scenarios to investigate the combined impacts of climate change and management on future SOC stocks in China's croplands. The model was run for croplands on mineral soils in China, which make up a total of 130 M ha of cropland. The model used climate data (years 2011–2050) from the FGOALS and PRECIS climate models based on four Intergovernmental Panel on Climate Change (IPCC) emissions scenarios. Three equidistant agricultural management scenarios were used. S0 was a current scenario, and S2 was an optimal scenario. Under the S2 scenario, crop yields increased annually by 1%, the proportion of crop residue retained in the field reached 90% by 2050, and the area of no-tillage increased to 50% of the cultivated area by 2050. Across all croplands in China, the results suggest that SOC will increase under all combinations of climate and management and that the effect of climate change is much smaller than the effect of changes in agricultural management. Most croplands in China showed a significant increase in SOC stocks, and only few zones, mainly in northeastern China, showed a decline. The maximum carbon sequestration potential of the croplands of China was 2.39 Pg C under S2. Annual increases in SOC stocks could offset a maximum of 2.9% of the CO2 emissions from fossil-fuel combustion in 2009.

Keywords: *Agro-C model, soil organic carbon, climate change, agricultural management, croplands*

Quantifying water volumes of ungauged lakes using optical satellite imagery and high-resolution LiDAR DEMs

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Abstract: Surface water bodies such as lakes, rivers and wetlands are critical water resources to both human and ecological systems, but are under increasing pressure from competing users. Monitoring of the location, quantity and movement of water is crucial in effectively managing these resources and implementing a sustainable water management strategy for the future. However, continuous information on the quantity and distribution of water across the landscape is limited in some regions because of the high cost of traditional in-situ monitoring. As such, global remote sensing datasets are being used more frequently to complement these sparse networks. This paper aims to develop new methods to estimate the quantity of water (volume) in open water storages such as lakes, using remote sensing data.

Lake Menindee, part of the greater Menindee Lakes complex in the Murray-Darling Basin, was selected as the case study of this research because of its geographic location and data availability. Water management in the Murray-Darling Basin has been under increasing scrutiny partly due to exposure of water theft by irrigators. As such, there is a pressing need for large scale monitoring of water resources in the region using novel data and methods.

This paper developed three methods to estimate water volumes in a lake, all of which only used a high-resolution (5m) LiDAR DEM in conjunction with optical imagery. As an initial preprocessing step, the water observations from space (WOfS) algorithm (Mueller et al. 2016) was applied to Landsat optical imagery to detect areas of surface water in the lake which was used as an input to all the methods. The first method derived a relationship between lake inundated surface area and volume using the DEM. Subsequently, this relationship was used to convert WOfS-derived surface areas to volumes. The second method evaluated the quality of match between the WOfS spatial inundation pattern and DEM-modelled inundation patterns at 0.1m water level increments, from which an optimal match and the respective DEM-derived volume was picked. Quality of match was quantified with three metrics commonly used in weather forecasting. In the third method, the elevation of the WOfS water body edge was derived from the DEM, and a volume was estimated by “filling” the lake DEM to this height.

Water volumes by all three methods were estimated using 19 years of high-quality Landsat data equivalent to 209 scenes, and daily gauged measurements were used for validation. A combination of scatterplots and statistical metrics were used for evaluation.

Initial findings show that all methods have reasonable skill in estimating water volumes with high Pearson correlation coefficients, and estimates from methods 2 and 3 have relative biases of less than 10 percent. No single method performed consistently better across all ranges of volumes, with method 3 having poorest performance for low volumes while method 1 substantially overestimated high volumes. Additionally, estimation errors were volume-dependent, with medium-range of volumes having highest accuracy estimates while prediction skill consistently worsened at higher volumes across all methods. Future research should further investigate drivers of the volume-dependent errors, expand the evaluations to multiple case studies, including the large on-farm water storages across the Murray-Darling Basin, and test other remote sensing data sources such as radar altimetry. These results clearly demonstrate the potential of remote sensing based methods for lake volume estimation.

Keywords: *Water volume, ungauged lakes, Water observations from space (WOfS), LiDAR DEM*

Surface water detection in areas with emerging vegetation using SAR data

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Abstract: Routine floodplain water mapping is pivotal to understand surface water dynamics and its interactions with the built and natural environment, groundwater resources, ecology, and the atmosphere. The 24-hour all-weather capability of Synthetic Aperture Radar (SAR) technology makes it a perfect choice for this application. SARs are active instruments that emit microwave pulses towards a target and measure the amount of microwave energy backscattered off an object. Radar backscatter is mainly a function of surface roughness and the different response of smooth water surfaces and rough water-free areas generally allows water surface mapping. However, the interpretation of the backscatter from vegetated areas has been identified as one of the biggest challenges in SAR image analysis.

Vegetation backscatter is the result of volume scattering from the canopy, diffuse scattering from the ground, and the double-bounce mechanism between the horizontal surface (ground or water) and the vertical structures (trunks or stems). In inundated areas, an increase in the double-bounce mechanism can lead to higher backscatter than that under non-flooded conditions. Optical sensors cannot detect standing water beneath vegetation; conversely, backscatter increase can represent the key factor enabling SAR to map surface water in areas with emerging vegetation. Nevertheless, a number of factors, including season, vegetation density, vegetation structure and microwave signal properties can complicate the expected backscatter change, hence, existing image interpretation algorithms rely on detailed field data and reference image(s). However, field data are rare, and despite the increasing availability of SAR acquisitions, adequate time series of reference images might not be readily available, especially for fine resolution acquisitions and observation of floods in fast moving catchments. To bypass this problem and make use of all the available SAR acquisitions, this study presents an algorithm for automatic flood mapping in vegetated areas, making use of commonly available ancillary data and a single SAR acquisition. First, probability binning is used for statistical analysis of the backscatter response of wet and dry vegetation for different land cover types. Second, this analysis is complemented with land use, morphology and contextual information within a fuzzy logic approach.

The proposed algorithm has been tested on a number of SAR acquisitions. The SAR-derived water surface layers retrieved from one ALOS-PALSAR and two COSMO SkyMed (HH polarisation) images acquired during the 2011 flood event in the Condamine-Balonne catchment (QLD) were validated using flood extent layers derived from optical images. The overall accuracy was found to be higher than 80% for all the images. Preliminary results on the analysis of Sentinel 1 data (both VV and VH polarizations) acquired during the 2017 flood in the Fitzroy catchment (WA) will also be presented.

The main benefit of the proposed algorithm is its capability to automatically detect inundated vegetated areas using a data parsimonious approach. Despite the difficulty of fully separating backscatter effects caused by flooding and forest canopy backscatter spatial variation, the promising results encourage further testing and the extension of the algorithm to incorporate experience in the use of reference images and multi-polarised data.

Keywords: *Surface water monitoring, SAR, emerging vegetation*

A global, near real-time system measuring river, lake, and reservoir dynamics

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Abstract: Measuring and predicting the dynamics of discharge in rivers and water storage in lakes and reservoirs can inform water management and policy decisions, flood management and response, and help understand the influence of climate change and anthropogenic activities on hydrological, biogeochemical, and ecological processes. However, water body dynamics are often poorly observed on the ground. Gauging networks are unevenly distributed and in decline globally, and much gauging data is not publicly accessible in near real-time, if at all. Remote sensing technologies provide a unique alternative to monitor changes in water extent, level and volume in space and time. Our aim was to develop a global monitoring system that provides near real-time river discharge and lake and reservoir storage information from satellite observations. To estimate river discharge, we derived global surface water extent fraction from the 8-day 0.05° resolution reflectance data from the Moderate Resolution Imaging Spectroradiometer (MODIS) and used recorded discharge at gauged sites and hydrological model estimates at ungauged sites to train MODIS-based satellite gauging reaches (SGRs) that can be used to estimate river discharge globally. In total, we were able to construct over 2,000 gauge-based and 11,000 model-based SGRs globally (Figure 1). To estimate volume changes in lakes and reservoirs, surface water extent dynamics for over 280 lakes and reservoirs (Figure 1) were derived from a daily 500-m resolution global surface water change dataset. Storage variations were calculated using surface water extent and height time series from the 10-day near real-time global lake and reservoir elevation dataset (G-REALM). As MODIS and G-REALM provide near real-time information, these data similarly allow estimation of river discharge and lake and reservoir storage in near real-time. It is hoped that the global monitoring system provides immediate and relevant information on rivers, lakes, and reservoirs, to inform government, the community and individuals on the current state of water resources in a historical context.

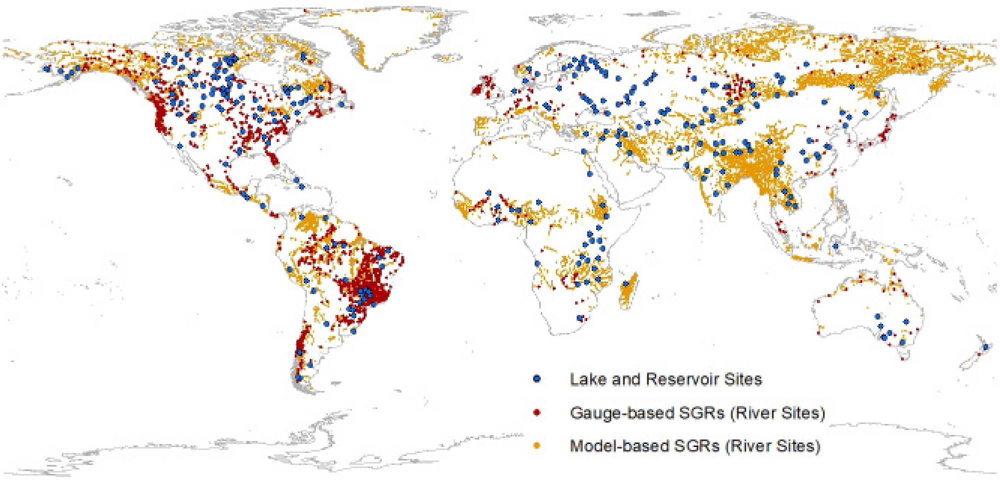

Figure 1. Global distribution of monitoring sites for rivers, lakes and reservoirs.

Keywords: *River discharge, lake and reservoir storage, global monitoring system*

EXTENDED ABSTRACT ONLY

Modelling river network topology from a perspective of riverine ecosystem services

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Abstract: River ecosystems exhibit unique forms and functioning that underpins the delivery of riverine ecosystem services (RES). These RES provide a multitude of benefits to the human race and are important to sustaining life on Earth. Approaches previously used to assess RES are limited to extreme weather patterns and climatic events, land use change, population and economic growth. The effect of geomorphological features that are important to the generation and delivery of RES through the River Network Topology (RNT) has been less explored. Previous approaches have either focused on ecological modelling of a single species or have quantified only one service among the range of RES. Such stand-alone approaches can be a limiting factor for river conservation and restoration efforts, as well as water allocation strategies within river basins. Therefore, an integrated approach that models RES and RNT to provide an estimation of changes in delivery of RES is suggested. In this study, we propose an integrated model that incorporates two important aspects of provisioning and regulating RES and presents the changes in RES by RNT.

We examine the performance of three different RNTs - long trellis narrow, inland dendritic and coastal dendritic topology on the delivery of six RES: water supply, sediment retention, nutrient uptake, hydropower generation, aquatic habitat provision and flood attenuation. We model RES using simple functional equations superimposed upon the different topologies. We then evaluate the sensitivity of RES to selected basin parameters (basin area, drainage density and basin slope) and compare among topologies.

This study shows that the three different synthetic river network topologies deliver different RES relative to one another. All the three topologies have a good capacity to retain sediment; the inland dendritic topology performs best in terms of providing both provisioning and regulating RES; and long trellis and coastal dendritic topologies are less suitable to attenuate floods and offer a less conducive environment for aquatic biota. However, the sensitivity analysis shows that physical habitat variability is sensitive to basin slope.

The results from the synthetic RNTs model indicates that river network topology plays an influential role on the spatial distribution and delivery of RES. Our next study will implement this model on ‘real world’ networks. The results from real river system will provide information that are applicable to implementing water related disaster preparedness, mitigation plans, corridor restoration, and environmental water allocation strategies.

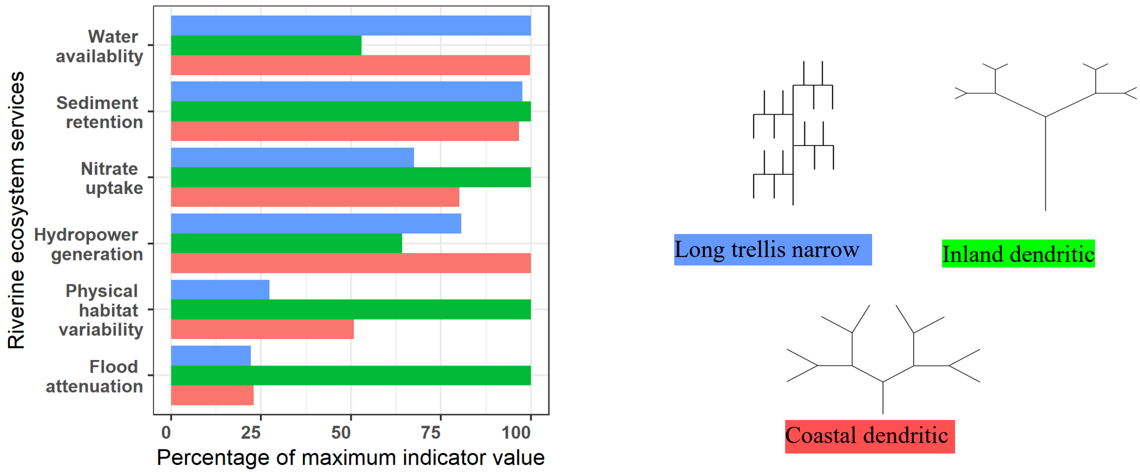

Figure 1. Riverine ecosystem services delivered by three different topologies

Keywords: *Modelling, river network topology, freshwater ecosystem services, river ecology*

Representation of river streamflow in China from land surface modellings and global reanalysis products

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Abstract: Traditionally hydrological modelling focuses on optimizing the accuracy of streamflow simulations through calibration techniques. While land surface models (LSMs) are often regarded as poor skills in simulating runoff because of biases in both meteorological forcing dataset and input parameters, as well as the uncertainties in the parameterization schemes. Global reanalysis products also provide the high spatiotemporal resolution of runoff dataset. However, they have not been well inter-compared and verification against the gauged streamflow in Chinese river basins. This study assesses the simulated routed runoff from five offline land surface models runs (VIC-CN05.1, CLM-CFSR, CLM-ERAI, CLM-MERRA, and CLM-NCEP) and three reanalysis datasets (ERAI/land, JRA55, and MERRA-2) against the gauged streamflow (26 stations) in major Chinese river basins during 1980-2008. The Catchment-Based Macro-Scale Floodplain model (CaMa-Flood) is employed to route those runoff datasets to the hydrological stations. Four statistical quantities including correlation coefficient (R), standard deviation (SD), Nash-Sutcliffe efficiency coefficient (NSE), and relative error (RE), along with a ranking method are used to quantify the quality of those runoff products. The results indicate that both modeled and observed streamflow in summer shows similarity in term of spatial patterns of climatology in most areas of China. The seasonal cycles of simulated streamflow at upper stream stations are relatively better than those at downstream stations. Among all products, the seasonal variability of streamflow from VIC-CN05.1, JRA55, and ERAI/land are more comparable to the observations than better than others. Except for MERRA-2, most of products are well reproduced the inter-annual variability of streamflow in both the Yangtze and Yellow River basins. The average normalized SD across all stations is 0.87 for JRA55 which is closest to the observations, followed by the VIC-CN05.1 (0.72). The average R values for all products are larger than 0.61 and the VIC-CN05.1 has the highest R value 0.85. According to the RE, the simulations are generally smaller than observations except for the VIC-CN05.1 and JRA55. In terms of NSE, the ERAI/land (0.41) and CLM-CFSR (0.26) perform relatively better than others. The runoff quality is highly related to the accuracy of precipitation in the atmospheric forcing datasets, and other metrological variables also affect the runoff simulations. Based on above statistics, the performances of eight runoff products are ranked in a descending order: VIC-CN05.1, ERAI/land, JRA55, CLM-CFSR, CLM-ERAI, MERRA-2, CLM-MERRA, and CLM-NCEP, which provide a reference for flood warning and hydro-climate research in the future. This analysis demonstrates the performances of offline LSMs simulations and reanalysis in representation of land surface hydrology, as well as the importance of development of long-term high-resolution surface meteorology datasets.

Keywords: *Runoff, land surface model (LSM), reanalysis data, CaMa-Flood routing model, observed streamflow*

Opportunities and challenges for integration of remote sensing and GIS into water take compliance regulation across the Murray-Darling Basin and coastal river systems in NSW, Australia

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Abstract: Water take compliance regulation across the New South Wales (NSW) Murray Darling Basin (MDB) shot to infamous prominence with the televising of the Australian Broadcasting Corporation (ABC) program 'Pumped' in July 2017. In response to the subsequent Matthews and Ombudsman investigations into NSW water management and compliance activities, the NSW Government established the Natural Resources Access Regulator (NRAR) to help restore public confidence and provide transparency in the way that compliance with water take limits is managed, assessed and enforced. This paper provides an overview of: (a) the role of NRAR in water take compliance across NSW; (b) case studies of remote sensing and GIS-based water take compliance assessment techniques applied in the MDB and coastal NSW catchments; and (c) a discussion of opportunities and challenges around effective and efficient integration of remote sensing and GIS analyses into water take compliance assessments across NSW.

Water take management in NSW is split across three agencies with: (i) WaterNSW as the water systems operator and licensor for NSW; (ii) Department of Planning Industry and Environment (DPIE) being responsible for the development of water plans, policies, accounting, modelling, take limits and access rules; and (iii) NRAR as the independent regulator responsible for monitoring, audit and enforcement of compliance with water take limits and rules. NRAR's role, therefore, is to monitor and audit water take, and where non-compliance is found, deliver graduated and proportionate responses to breaches of water law to ensure effective, efficient, transparent and accountable compliance and enforcement of water take limits and access rules.

Integrated remote sensing and GIS analyses, together with hydrograph analyses focussed on water pumping signatures, undertaken in-house and in collaboration with the Murray-Darling Basin Authority (MDBA) and DPIE (Water), now form a highly successful and routine part of NRAR water take compliance assessment procedures. Integrated remote sensing and GIS analyses of water licensing and accounting data are used to inform both real-time 'boots on the ground' operations designed to protect specific environmental flow events as they occur, as well as water use audits across large areas for targeted compliance checks of properties that appear as 'outliers' with regard to water entitlement or usage volumes. Standard remote sensing and GIS analysis techniques including thresholding, image differencing and zonal statistics, are applied to vegetation, water and moisture indices calculated from Sentinel Level 1C and Landsat Level 2A data to quantify irrigated cropping areas, changes in dam surface water extent and changes in crop and soil moisture levels. These remote sensing, GIS and hydrological analyses are then integrated with water licensing and accounting databases to identify targets for field-based compliance checks.

Free public access to Sentinel level 1C and Landsat level 2A satellite imagery has provided an outstanding opportunity for deep integration of remotely sensed data into GIS based analyses of water take compliance at daily, seasonal and annual time steps across NSW and the MDB. A key challenge for NSW and other MDB states, however, lies in both ensuring the data integrity of, and enabling the spatial integration of, legacy water licensing and water accounting databases and systems that were never designed for spatially-based water take analyses. Progress in resolving these legacy database challenges will not only improve our understanding of compliance with water take limits and rules, particularly during drought years when public concern and scrutiny over water management is greatest, but improve our understanding of water balance accounting and water management across the MDB.

Keywords: *Remote sensing, GIS, Sentinel, Landsat, water take compliance and regulation*

Wetland dynamics from combined optical and radar satellite observations

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Abstract: Wetlands are covered by a complex mix of open water, inundated, wet and dry, vegetated and bare surfaces. Changes in the spatial distribution of cover types in response to weather and climate conditions affect a wetland system's ability to support habitats and serve hydrological functions. Systematically acquired satellite observations have proved to be valuable for mapping seasonal and long term variation of land covers and in turn help characterize wetland systems. Digital Earth Australia's extensive optical earth observation archive has been used to map open water, wet and dry vegetation across Australia for the last 30 years. Despite this success, significant challenges exist in monitoring wetlands with optical data alone, including accurately differentiating inundated vegetation from dry vegetation in routine observations, and the loss of optical observations due to cloud cover during wet periods when changes often occur rapidly.

In this work, we investigate using Sentinel-1 synthetic aperture radar (SAR) time series data in combination with Landsat optical data to map wetlands in Australia. Sensitive to surface roughness and moisture content, SAR observations provide complementary information to reflectance and color measured by optical sensors. From late 2016, Sentinel-1's two-satellite constellation has been acquiring data over Australia every 12 days, providing more than 2 years of regular observations with little impact by weather.

Open water in wetlands is effectively mapped by SAR due to low backscatter from specular reflection. We show this by using unsupervised clustering algorithms to differentiate open water from vegetation. Our other focus is inundated vegetation that produces a strong backscatter signature through a double-bounce scattering mechanism. In addition to single scene classifications, temporal analysis is employed to constrain changes related to water extent, vegetation structure and moisture content.

We show that Sentinel-1's regular observations are critical to capture highly dynamic changes, especially in the tropical environment. Combining SAR derived mapping with vegetation status and wetness measures from optical data, we are able to compile a detailed picture of cover changes for our study areas. This picture is compared to weather records and information of environmental events to qualitatively assess its accuracy.

Keywords: *Wetlands, Synthetic Aperture Radar, Sentinel-1, Landsat*

Improving current estimates of global water and energy budgets

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Abstract: There is a growing recognition of the improved accuracy offered by hybrid observational estimates incorporating a range of different observational sources over single-source estimates. Many merging and/or data assimilation techniques have already been developed to derive such products. While in-situ observations are often the only direct measurements for many variables of interest, they are typically underrepresented in most hybridization approaches, particularly in computing uncertainties in single and hybrid estimates. This is despite the heavy reliance of data merging and assimilation approaches on such information. The reason for this is mainly the limited temporal and spatial availability of in-situ observations, and also the lack of confidence in their ability to represent the grid scale of the hybrid or single source products.

We present a framework that implements a novel merging technique along with an existing data assimilation technique that we use to derive coherent, conserving estimates of the components of the surface water and energy budgets. Our framework uses available in-situ observations to an extent that has not been used before. This includes defining a metric of performance of the employed individual estimates, measuring the dependence between them and computing their spatiotemporal uncertainties. The derived hybrid estimates are more observationally constrained than any of the employed products. Additionally, we incorporate the physical balance constraints of the water and energy budgets into a data assimilation technique to further adjust the hybrid estimates.

We also give compelling evidence that suggests that in-situ observations provide useful information at the half-degree grid scale, for a range of different variables. We also show that the derived hybrid estimates outperform the single-source estimates, and that the additional conservation constraints offer further improvements across a range of metrics. Our framework, aside from being able to eliminate incoherence between available components of water and energy budgets, provides a tool for evaluating the quality of individual water or energy budget component estimates, assessing the harmony between budget variables, and comparing various estimates of the same budget variable at the grid scale, regardless of whether in-situ observations are lacking or not. This is particularly important because it allows us to make a step forward towards addressing the problem of evaluating global products over regions with no direct observations.

Keywords: *Merging, data assimilation, hybrid estimates, uncertainty, energy budget and water budget*

Observation-constrained prediction of the response of whole soil profile carbon to warming across the globe

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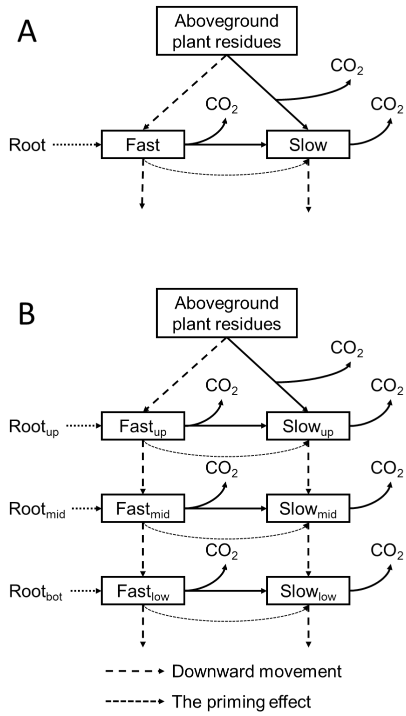
Abstract: The response of global soil organic carbon (SOC) stock to warming regulates carbon cycle-climate feedbacks. Although SOC in topsoils above 0.3 m has been comprehensively studied, the response of SOC in the whole soil profile to warming has never been explicitly quantified at the global scale. Here I combine soil carbon models constrained by global observational databases with machine learning to predict the response of whole soil profile SOC (down to 2 m) to warming across the globe at 1 km resolution. The observation-based global database WISE30sec was used to derive SOC stocks in three sequential layers down to 2 m across the globe. The global MODIS NPP dataset at the 1 km resolution was used to estimate carbon input (including aboveground plant residues and root-derived carbon substrates) into the soil. I modelled the 0–2 m soil profile as a single layer using a single-layer model (Fig. A) and as three soil layers, i.e., 0–0.2, 0.2–1, and 1–2 m, using a multi-layer model (Fig. B). First, a model spin-up run was conducted for both models until reaching an equilibrium state with the modelled SOC stocks match the observed SOC stocks under the carbon input estimated based on the MODIS NPP dataset. After reaching the equilibrium state through above spin-up run, then, the soil was perturbed from the equilibrium state assuming a warming event. And the model was run until reaching another equilibrium state under the warming event. The SOC change under the two equilibrium states using the two modelling frameworks (Fig. A vs Fig. B) was calculated, and compared under different scenarios taking into account downward movements of SOC, potential carbon input changes and uncertainty in the temperature sensitivity of carbon pools.



The results demonstrate that negative effects of warming on SOC extend to deeper soil layers over the world. When SOC reaches a new equilibrium state under 2° warming assuming no carbon input change, the model predicts a 6% (which is equivalent to 123.6 Pg C) decrease in global SOC stock in the 0–2 m soil layer, to which the 0–0.2, 0.2–1 and 1–2 m soil layers contribute 23.5%, 38.1% and 38.4%, respectively. To offset this decrease, a 6.8% increase of carbon input is required. Furthermore, I find that downward movement of SOC along the soil profile increases the resilience of SOC to warming. Under a scenario of no downward movement, the predicted decrease of SOC stock under 2° warming without carbon input change is increased to 17.6%, while the carbon input required to offset this SOC decrease is shifted up to 21.6%. Using a machine learning approach combining the model simulation results, I mapped the spatial pattern of SOC change in different soil layers under warming across the globe at the resolution of 1 km. This study provides the first estimation of whole soil profile SOC change under warming and additional carbon input required to offset the change across the globe, and suggests that downward movement of SOC moderates the sensitivity of SOC stock to warming although additional carbon input is a prerequisite to offset the negative effect of warming on SOC stock. The map is particularly useful to identify hotspots where SOC are sensitive to global warming and thus help the development of mitigation strategies.

Keywords: *Soil carbon cycle, data assimilation, temperature sensitivity, warming*

Assimilating streamflow observations into forecasting models by combining state and output updating

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Abstract: Streamflow forecasts with lead times of hours to days are useful for a wide range of applications. Errors in streamflow forecasts arise from errors in hydrological model process representation and initial conditions, and from forecast forcing. Data assimilation seeks to reduce hydrological modelling errors by updating output, state variables, forcing or parameters. Most streamflow forecasting systems globally tend to use output updating, or error correction, methods as they are highly effective in reducing forecast errors at short lead times and are relatively simple to implement.

Output updating methods tend to address the symptoms of forecast errors rather than the underlying cause, and therefore their effectiveness can diminish has lead time extends. Methods that update model input, state variables or parameters seek to reduce the underlying cause of forecast errors, but may be less effective than output updating methods at correcting errors at short lead times. Few studies have compared or combined state and output updating methods. In this study we compare the effectiveness of state and output updating schemes in reducing errors in streamflow forecasts. We introduce an approach that combines state and output updating. Hourly semi-distributed hydrological models that combine the GR4H rainfall-runoff model and Muskingum channel routing are used. Streamflow forecasts are generated by forcing the initialized hydrological model with ensemble rainfall forecasts generated by pre-processing ACCESS-G predictions and with perfect (observed) rainfall.

We use a particle filter to update the state variables of the hydrological model. Particles are generated by perturbating precipitation and evapotranspiration forcing, and the state of the production and routing stores of the GR4H. A likelihood function based on a transformed normal distribution and evaluated over a multi-day assimilation window is used to compute particle weights. A sampling importance resampling approach is adopted to prevent ensemble degeneracy.

We use the ERRIS hydrological error model to describe hydrological simulation errors and update streamflow forecasts. ERRIS reduces hydrological simulation errors after transformation using a conditional bias correction and an autoregressive model. Residuals are then described with a mixture of two normal distributions. We estimate ERRIS parameters using streamflow simulations generated with and without state updating.

We evaluate the performance of hourly cross-validated streamflow forecasts for lead times of up to 10 days. The forecasts cover 6 years between 2010 and 2016 for 8 Australian catchments. Updating state variables reduces forecast errors before output updating is applied by up to 40%. Output updating can reduce forecast errors to near zero at short lead times, but as lead time extends forecast errors increase. Forecasts generated by combining state and error updating tend to have the lowest errors at all lead times and are the most reliable. Updating state variables not only reduces simulation errors but also makes them more predictable, meaning that output updating methods are more effective and are applying smaller corrections. However, the effectiveness of data assimilation is strongly dependent on the hydrological characteristics of a catchment, with small and fast responding catchments benefiting less than larger and slower responding catchments. Further work is required to optimize the data assimilation process for operational applications.

Keywords: *Particle filter, coupled assimilation, ensemble streamflow forecasts*

Assimilating satellite soil moisture retrievals to improve operational water balance modelling

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Abstract: A simple and robust method for assimilating satellite soil moisture (SM) products into the Australian Water Resources Assessment (AWRA) model was developed and tested via the community modelling system, AWRA-CMS. The method requires time series of two satellite soil moisture products, along with AWRA simulations of upper-layer soil water storage for an offline determination of weights for use in the optimal merging of models and observations via the triple collocation (TC) technique. The candidate data sources were near real-time products from the Soil Moisture Active/Passive (SMAP), Soil Moisture and Ocean Salinity (SMOS), and Advanced Scatterometer on MetOp satellite (ASCAT) production systems.

Evaluation of AWRA model performance with and without data assimilation (DA) was conducted for key variables including upper-layer soil water storage, root-zone soil water storage, evapotranspiration and streamflow against in-situ networks. The comparisons demonstrated conclusively that the assimilation of satellite SM considerably improved the accuracy and representation of AWRA model surface soil moisture across Australia. The temporal correlation was increased by 0.2 correlation units on average after the assimilation compared to open-loop across in-situ SM monitoring sites. Positive impacts were found on the simulation of streamflow over majority of catchments with an increase in correlation by up to 0.4. The impact of SM assimilation on the other variables was not as significant, largely as a result of the indirect way SM assimilation imparts constraint on those variables.

Finally, an investigation into the impact of SM data assimilation on forecast accuracy was conducted through driving AWRA model with forecast meteorological forcing 9 days into the future. Improved skill in estimating surface soil moisture of AWRA were found to persist up to 4 days, and likely longer. Results of this study demonstrated the benefit of constraining model outputs with satellite soil moisture observation on improving model simulation, as well as the importance of accurate initial hydrological states on improving forecast skill. Improved SM is vital for assessing and predicting water availability and assisting policy making.

Keywords: *Data assimilation, soil moisture, water balance model*

Remote sensing estimation of the soil erosion cover-management factor over China's Loess Plateau

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Abstract: Soil erosion and land degradation are primarily triggered by the reduction of vegetative cover of soil surfaces due to inappropriate management practices by human or natural hazards. The cover-management factor (C-factor) is used in the revised universal soil loss equation (RUSLE) to represent the effect of vegetation cover and its management practices on hillslope erosion. Satellite data have been widely used to estimate vegetation cover and the C-factor, but few studies have used fractional vegetation cover (FVC) for time-series estimation of the C-factor for large areas. In this study, we estimated and mapped monthly C-factor across China's Loess Plateau for a continuous period of 17 years (2001-2017) using time-series FVC products, including photosynthetic vegetation and non-photosynthetic vegetation, derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) and weighted by monthly rainfall erosivity ratio. We further analysed the spatio-temporal variations of FVC and the C-factor over the Plateau and delineated the potential high erosion risk areas. Our study reveals a significant increase in total vegetation cover from 56.0% to 76.8% (with a mean of 71.2%), resulting in about 20% decrease in the C-factor and erosion risk during the 17-year period. Our results were compared with published studies and estimates from cloud-free Landsat images (13,801 scenes) showing similar patterns and trends (Figure 1). Methods have been successfully implemented in geographic information system and Google Earth Engine platforms which can be used as efficient tools to continuously and consistently monitor vegetation cover, erosion risk and climate impacts.

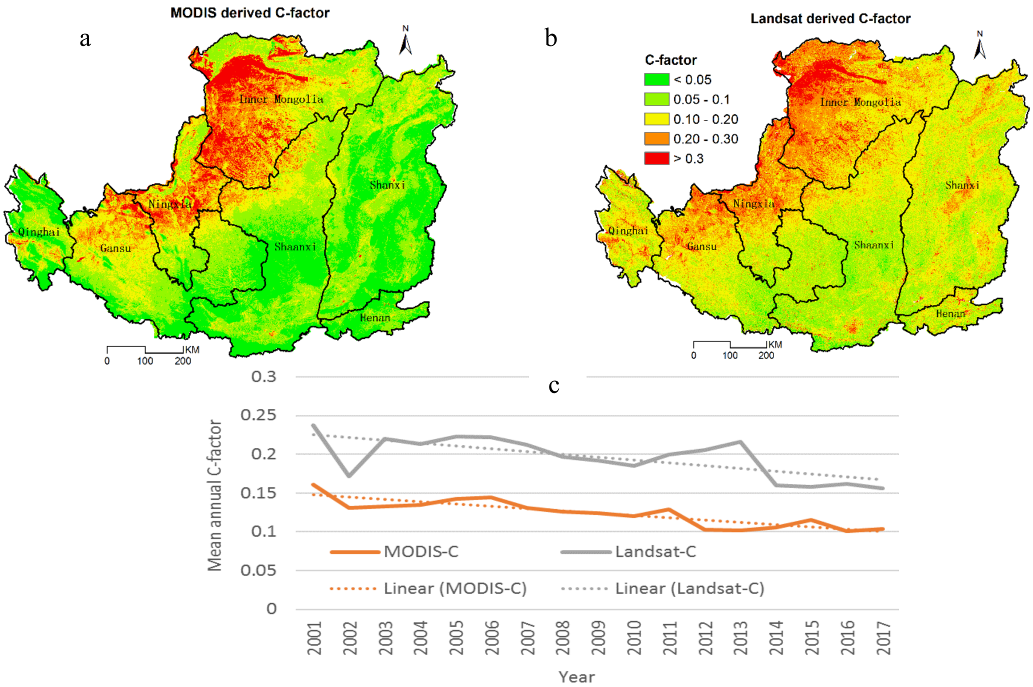

Figure 1. Comparison of MODIS derived C-factor with Landsat derived C-factor over the Loess Plateau, a: MODIS derived annual C-factor, b: Landsat derived C-factor, c: changes of C-factor in period 2001-2017 estimated from MODIS and Landsat.

Keywords: *Soil erosion, cover-management factor, remote sensing, fractional vegetation cover, Loess Plateau*

Insights into the role of fire geometry and violent pyroconvection

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Abstract: Violent fire-driven convection can manifest as towering pyrocumulus (pyroCu) or pyrocumulonimbus (pyroCb) clouds. These events, which can have devastating impacts on the environment and society, appear to be a worsening problem. The main concern is that their associated fire spread is erratic, unpredictable and not generally suppressible. Research into large pyroconvective events has mainly focused on the atmospheric processes involved in normal atmospheric convection, or on surface fire weather and associated fuel conditions. There has been comparatively less attention paid to the role of the fire itself in these coupled fire-atmosphere events.

This paper draws upon recent insights into dynamic fire propagation and extreme wildfire development to investigate how the condition of the fire influences the occurrence of violent pyroconvective events. Specifically, the Weather Research and Forecasting Model (WRF) is used to examine how the fire geometry may affect the likelihood of pyroCb occurrence. WRF simulations are used to quantify the role of the spatial expanse, intensity of a wildfire and the presence of wind, in the development of large pyroconvective plumes. The initial work presented here utilises a static heat source of variable dimension and intensity.

The analyses indicate that the shape and intensity of large fires are critical factors driving the development of pyroconvective plumes. These findings provide motivation for further investigation into the effect of the fire's attributes on the immediate atmosphere, and have the potential to improve forecasting of blow up fire events.

Keywords: *Wildfire modelling, fire-atmosphere interaction, deep flaming, pyroconvection, pyrocumulonimbus*

Empowering strategic decision-making for wildfire management: the methodology of polygons of fire potential

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Abstract: As more complex scenarios for fire management arise, the operational capacity of fire services is more frequently overwhelmed by fires that exhibit extreme behaviours. Moreover, there is an increased number of Wildland-Urban Interface (WUI) communities settled in the path of fires, and thus protecting people's lives and property becomes a priority. Such scenarios have caused fire services to become more reactive and defensive in operational response to face certain risks, as opposed to adopting proactive and strategic decisions to face uncertain risks. Firefighting experience in the Mediterranean region over the last decades demonstrates that traditional fire suppression activities have been successful under certain and predictable scenarios, but fail when it comes to uncertain and dynamic scenarios (e.g. Chile in 2017, California in 2017 and 2018, and Portugal in 2017). The identification of multiple sources of uncertainty, together with the development of organizational resilience within the response system, become formidable challenges.

The presentation will discuss a methodological approach based on the identification of polygons of fire potential. This is a methodology that has been directly formulated by the fire community and has been already implemented in some parts of Europe and other regions of the world. Polygons of fire potential incorporate uncertainty to the decision-making process in that they enable the fire manager to decide the final result of the fire by identifying what can burn, what can be saved, and what will be lost every time they make a decision. The method consists of depicting the fire spread potential by segregating the landscape into distinct spatial units (polygons), each presenting homogeneous fire behaviour characteristics. Operational possibilities are limited inside polygons, which means that every time that fire enters a polygon the entire polygon becomes untenable. However, the connectivity between polygons becomes a window of opportunity to stop the fire from spreading from one polygon to another and thus enables the fire manager to decide the final result in terms of fire spread.

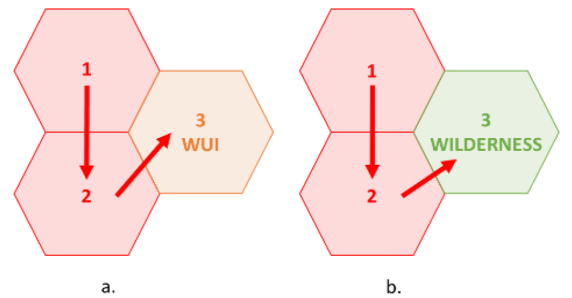

Figure 1. Polygons of fire potential. Red arrows represent the path of fire.

Strategic decision-making varies according to the values contained in each polygon of fire potential. Figure 1 depicts how a scenario can change when fire spreads from polygon 1 to 2 and fire services focus on preventing the spread of fire from polygon 2 to 3 (which has different associated values). In scenario (a) fire services will endeavour to protect polygon 3 at all cost as the at-risk values in the WUI are people and properties. This keeps certainty for fire services because the decisions taken to achieve the objectives are aligned with the accepted at-risk-values approach (from highest to lowest priority: people, properties and environment). In scenario (b), the decision to protect the wilderness would come with a high level of uncertainty because the objectives and the risk assumed by the fire services are not aligned with the accepted at-risk-values approach. In this case, the decision to let the wilderness region burn will have a social impact, and therefore pedagogy will become necessary to convey to the public the positive and negative impacts of fire on that ecosystem.

Keywords: *Uncertainty, at-risk values, polygons of fire potential*

Hydrodynamic modelling of a drinking water reservoir to assist in bushfire impact mitigation and recovery

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Abstract: The majority of Melbourne's drinking water supply comes from fully protected forested catchments and as a result water is supplied to customers disinfected but not filtered. Decreases in raw water quality can affect the efficacy of the chlorine disinfection as well as reduce the aesthetic quality of the water and therefore bushfire is a major threat to Melbourne's water supply.

In early 2019 a bushfire, sparked by dry lightning, started in the Thomson Reservoir catchment. The Thomson Reservoir is Melbourne's largest reservoir with a capacity of over 1,000GL. The fire burnt a total of 13% of the 48,700 ha catchment. Areas on the edge of the reservoir, close to the offtake point, and on the major feeder stream were most impacted. This event significantly increased the risk of a large erosion event, known as a debris flow, which could have a considerable impact on water quality in the reservoir. The use of models and modelling expertise provided invaluable decision support which helped ensure the quality of Melbourne's drinking water was maintained both during and following the fire.

The areas within the catchment with the greatest potential to generate debris flows following a fire were mapped using the rapid risk assessment tool (RRAT) (Sheridan, GJ, Lane, PN, Smith, H & Nyman, P (2009) *A rapid risk assessment procedure for post-fire hydrologic hazards; 2009/10 fire season*. Technical report produced for the Department of Sustainability and Environment. The Department of Forest and Ecosystem Science, The University of Melbourne, Australia). These maps were overlaid with actual fire burn intensity maps to determine the location of highest risk of debris flow. The location, load estimates and debris flow composition were used as inputs into the three dimensional hydrodynamic model of Thomson Reservoir.

The Aquatic Ecosystem Model (AEM3D) was used to model reservoir hydrodynamics and the fate and transport of the particles entering the reservoir following a debris flow. The model is forced by meteorological data, including wind, as well as inflows and outflows. Previous studies have successfully calibrated the models being used. Modelling improved knowledge of reservoir hydrodynamics, including the behaviour of fine sediments. This aided in quick short-term decision making. One immediate mitigation measure involved moving the offtake level lower down in the water column in the impacted reservoir in order to avoid the higher turbidity water at the surface. Another operational decision was to artificially mix the reservoir downstream of Thomson Reservoir to increase dilution and prevent short-circuiting of water from the fire affected reservoir. Modelling helped to show the benefits of these actions and also give an understanding as to when those benefits would be realised.

Hydrodynamic modelling was also used to quantify the impact of transferring poor water quality on downstream reservoirs. Water quality thresholds were then determined for different transfer rates and total volumes. This information was included in operational and contingency plans to provide a clear guide to operations staff. It ensures that the maximum amount of water can be utilised without detrimentally impacting downstream water quality. Longer-term water resource impacts were also of concern. Hydrodynamic modelling was used to propagate the known volume of sediment, in a worst-case scenario, through the reservoir. This provided information to water resource managers about the likely amount of time that the reservoir would have to be taken off-line due to poor water quality and subsequently, the volume of water that would need to be supplied from alternate sources.

Improved understanding of the hydrodynamics of the reservoirs, including the impact of debris flows, and better quantification of the risks to water quality, enables more informed decisions around event mitigation and recovery planning. This will help ensure that Melbourne remains supplied with safe drinking water in the face of bushfire threats.

Keywords: *Hydrodynamic modelling, bushfire, drinking water*

Climate change increases the potential for extreme wildfires

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Abstract: Pyrocumulonimbus (pyroCb) wildfires cause devastation in many regions globally. Given that fire-atmosphere coupling is associated with pyroCbs, future changes in coincident high index values of atmospheric instability and dryness (C-Haines) and near-surface fire weather are assessed for southeastern Australia using a regional climate projection ensemble. We show that observed pyroCb events occur predominantly on forested, rugged landscapes during extreme C-Haines conditions, but over a wide range of surface fire weather conditions. Statistically significant increases in the number of days where both C-Haines and near-surface fire weather values are conducive to pyroCb development are projected across southeastern Australia, predominantly for November (spring), and less strongly for December (summer) in 2060-2079 versus 1990-2009, with future C-Haines increases linked to increased 850 hPa dewpoint depression. In several locations, increases are in the range of 4-5 days on average. These increases are projected to occur over areas that include agricultural regions and near urban areas. Such changes are almost entirely absent during 2020-39 versus 1990-2009. C-Haines is a better indicator of pyroCb development than surface fire weather conditions. The extension of the season conducive to pyroCbs into spring is important because currently Australian pyroCbs are typically summer phenomena and a change in seasonality has implications for resource allocations of fire agencies. The increased future occurrence of conditions conducive to pyroCb development and their extension into spring have implications for mitigating these dangerous wildfires and urbanising fire-prone landscapes.

Keywords: *Atmospheric instability, dewpoint depression, fire weather, natural hazards, pyrocumulonimbus, regional climate modelling*

Investigation of plume attachment in inclined terrain profiles

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Abstract: Developing a comprehensive understanding of the behaviour of hot plumes associated with fires burning in steep and confined terrain is an important issue for firefighter safety. Many fatal accidents and incidents involving serious injury to firefighters (e.g. burnovers) occur on steep slopes or otherwise complex terrain. Many of these instances involve the fire escalating abruptly and unexpectedly, catching even experi-enced firefighters off guard.

Previous studies have linked these instances to dynamic modes of fire spread such as fire eruption, but the precise mechanisms driving them are still not properly understood. A number of authors have suggested a role for flame, or plume, attachment driven by the Coandă effect, which is a hydrodynamic effect that causes the flames and plume of a fire to attach to a sufficiently inclined surface. The Coandă effect has been implicated in structural firefighting disasters like the 1987 King's Cross disaster.

In the present research, we use Computational Fluid Dynamic methods to extend previous work that considered plume dynamics for fires burning in trenches within a confined tunnel. Specifically, we consider the plumes of open fires burning on slopes with various topographic profiles. Note that by 'open' we mean domains without a roof, in contrast to tunnel conditions. These open scenarios are more representative of the conditions encountered when wildland fires burn in complex terrain. We report preliminary results for fires burning in channels with 90° and 45° sidewalls.

Results from this study suggest the Coandă effect causes an otherwise rising plume, driven purely by convection, to attach to open channel surfaces for many metres ahead of fire fronts in terrains of slope above 26°. Accordingly, strong updraughts may follow channels and fan a fire's spread along eroded gullies and dry creek beds of sloping terrains and notably in directions totally divorced from that of regional winds.

Slight variations in the attachment threshold were found for different fire source energies and channel profiles which is consistent with the 26° threshold identified for rapid attachment to channel surfaces in tunnels, i.e. at the early tunnel fire phase prior to support from updraughts.

Keywords: *Plume attachment, firefighting, trench effect, CFD, fire dynamics, Coandă effect*

Quantifying dynamic fire behaviour phenomena using Unmanned Aerial Vehicle technology

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Abstract: Catastrophic wildfires are often a result of dynamic fire behaviours. Although some of these behaviours have been described and investigated, others require further study. Fire coalescence and junction fires are particular cases of merging fire fronts and are common phenomena observed during bushfires. They are important as they can cause rapid escalation of fire behaviour and be dangerous for ground-based emergency personnel. There are a few studies devoted to investigation of merging fires in field conditions. There is a need for high temporal and spatial measurements of fire behaviour in field conditions in order to better understand this phenomenon and evaluate risks during bushfires and prescribed burning. The aim of this study was to test emerging technologies for better quantification of fire behaviour at field scales and evaluate their potential as an operational tool.

Several small and medium scale field experiments were conducted during April 2019 on farmland in Victoria, Australia. Harvested wheat fields were used as experimental plots, as they form relatively homogeneous fuel beds. Fuel height varied from 18 to 40 cm with fuel load and moisture content at 1.1 t/ha and 11.9 % respectively. Wind speed varied in the range of 1.5-6.5 m/s. An Unmanned Aerial Vehicle (UAV) was used to capture high definition video imagery of fire propagation in synchronisation with sensor data from the on-board Global Positioning System (GPS) and Inertial Measurement Unit (IMU). These sensors enabled the platform/camera orientation and position in space to be aligned with the video footage of fire propagation and to be georeferenced in GIS software.

Twenty-one junction fires and five inward parallel fire fronts (parts of the fire lines approaching each other) were identified during the experiments. The rate of spread (ROS) of merging fire fronts was found to be at least two times higher than for the basic fire fronts (the rate of spread of a linear fire front in the same fuel bed in no-slope conditions) and for junction fires with acute angles (< 14°) it increased 6 times and more. Inward parallel fire fronts spread much slower, varying between 0.05 and 0.25 m/s. Forty-six percent of junction fires had increase of the ROS at the final stage of the merging process in contrast to Thomas et al. (2017) and Viegas et al. (2012). Also, it was observed that the angle between two oblique fire fronts did not change significantly in time for the initial angles smaller than 34°. It can be assumed that the main fire front influences on the shape and ROS respectively of junction fires and laboratory experiments cannot fully replicate these conditions.

Although the initial experimental conditions were very different in relation to scale, fuel and wind conditions, similar ROS to that shown in numerical simulations by Thomas et al. (2017) were observed in our field experiments. Further investigation is required to explain the similarities as the relationship between fuel load, wind speed and scale is not known. The comparison of corrected values of dimensionless ROS for different angles between fire fronts with laboratory experiments of Viegas et al. (2012) showed reasonable quantitative agreement.

These experiments have shown that the method of using UAV's to capture georeferenced video footage can be used reliably to quantify fire behaviour phenomena for research, operation and management purposes.

Keywords: *Remote measurements, UAS, fire front propagation, merging fire fronts*

Wildfire risk assessment using the Cloud

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Abstract: Wildfires are devastating natural phenomena and considerable effort is undertaken to mitigate their impact. Underpinning the planning of mitigation efforts is an understanding of the likely outcomes of a wildfire such as the area burnt, the intensity of the fire and the impact on sensitive areas. However, these outcomes will change for fires at different points in the landscape as well as different fuel or weather conditions. To test various mitigation strategies all of these factors must be taken into account, which can lead to a large matrix of scenarios which must be tested. While computational wildfire simulators can provide a prediction of outcomes for a single scenario at a speed much faster than real-time, the total number of simulations currently provides a limiting factor for large-scale risk assessments if these are computed on a single computer or server.

The Cloud, in contrast, provides scalable access to almost unlimited computational resources. We have implemented a scalable Cloud implementation for wildfire risk assessment allowing the creation of a scalable number of jobs, each representing one simulation, over the Cloud (Figure 1a). The architecture for the framework has four main components: a Master, multiple Workers, a Web Client and a Queue. The creation, starting, stopping and updating of jobs is controlled by the Master. Once a job is started it is pushed to the Queue, which is polled by Workers for incoming jobs. When a job is received by a Worker, any job files are downloaded from the Master, a simulation is run using the Spark wildfire framework and results uploaded to Amazon 'S3' cloud storage. The Web Client is used to configure and trigger these jobs and to visualise the simulation output. To allow easy deployment and operation, the framework is containerised into Master, Workers and Queue instances. These containers can be deployed with cloud orchestration tools like Kubernetes or Docker Swarm. This allows automatic provisioning of resources, auto-scaling and failure recovery.

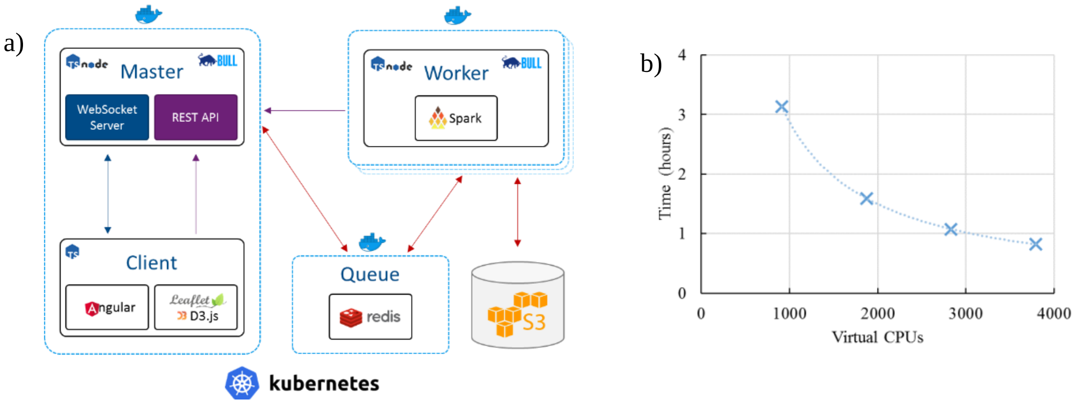

Figure 1. a) Architecture for the Cloud framework, b) Time taken for 68,047 simulation as a function of number of virtual CPUs on Google Cloud.

The framework was applied to a spatial risk assessment over the state of Tasmania based on the Bushfire in Tasmania (2014) methodology. Multiple independent wildfires were simulated with gridded ignition points spaced 1 km apart across the state resulting in 68,047 individual wildfire simulations. The wildfire simulations ran for 8 simulated hours at 30 m resolution, used the TASVEG land classification map and six rate of spread models including eucalypt, grassland, buttongrass and heathland. The 'worst case' weather streams from the methodology were used. The resulting time taken for the entire risk assessment is shown in Figure 1b as a function of number of virtual CPUs on the Google cloud. The system can be scaled to thousands of compute nodes with corresponding decrease in the compute time for the entire set of simulations, with the largest number of nodes used, 3792, taking 49 minutes to complete. The framework represents a step forward in the ability to compute large scale risk assessments, and the Cloud computation framework could allow such analysis to be carried out on a routine basis for fire management and risk mitigation purposes.

Keywords: *Risk assessment, Cloud computing, wildfire simulation, Spark*

Physics-based simulations of fire development downstream a canopy

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Abstract: Large eddy simulations of grassland fires propagating downstream of a tree canopy were carried out to study the effect of large-scale canopy-induced flow structures (essentially gusts) upon the fire spread dynamics. The simulations were conducted using FireStar3D – a physics-based model that solves the conservation equations of the coupled system consisting of the vegetation and the surrounding gaseous medium. The model accounts for the different physico-chemical processes taking place in a wildfire (Morvan et al., Fire Safety J., 101, 2018). A 10 m high canopy was considered with variable vertical distribution of the leaf-area-density. The simulations were carried out for a leaf-area-index of 0.5, 2, and 8, and for an average 10-m wind speed U_{10} = 1, 3, 5, 8, and 12 m/s. A 50 m high and 50 m wide computational domain was considered, with periodic conditions at the vertical lateral boundaries to simulate a quasi-infinite fire front (see Fig. 1). A 50 m long canopy section was considered at the domain entrance, and the inlet conditions were obtained from precursor simulations of atmospheric boundary layer flow over a homogeneous canopy, that were run long enough to obtain a statistically-steady flow with the desired average 10-m wind speed. For these precursor simulations, a wave number and frequency analysis were performed for the normalized streamwise velocity at the canopy surface, obtained at steady state. The analysis showed that the spectrum amplitude decays exponentially with the normalized wave-number with a slope of about -1, and decays according to a power law with the Strouhal number with a slope of about -3. Then, before fire ignition, we investigated the flow redevelopment distance downstream the canopy for different wind speeds, and the results showed that the redevelopment distance exceeds 30 times the canopy height for all considered cases. Finally, the rate of spread, and the fireline intensity were reported at different positions downstream the canopy and compared to those obtained in the case of an open grassland (without a canopy) with the same fuel properties. The results showed a significant damping effect of the canopy on both the rate of spread and the fire intensity, with a reduction that exceeds 50% in some cases. In addition, fire extinction was observed at U_{10} = 1 m/s, which was not the case of an open grassland fire. Also, particular attention was devoted to the flames fluctuations and to their correlation to the canopy-induced flow structures.

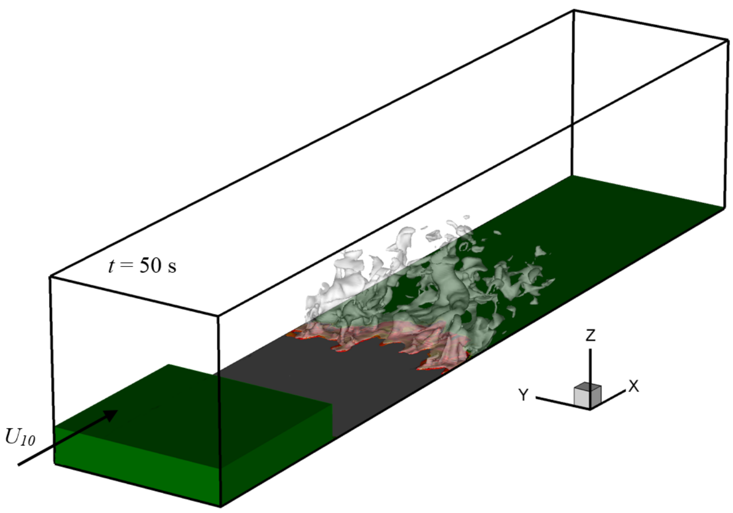

Figure 1. Computational domain and solution of fire propagation downstream a canopy obtained for an average 10-m wind speed U_{10} = 8 m/s, 50 s after fire is ignited along the canopy edge. Fire is visualized by an isovalue surface of the soot volume fraction (10^{-6}) colored by the gas temperature and by an isovalue surface of the water mass fraction (0.0075) in grey with 50% of transparency.

Keywords: *Wildfires, physics-based fire simulation, surface fire, tree canopy*

Victorian fire weather trends and variability

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Abstract: Information on the trends and variability of fire weather indices and weather variables has a wide variety of applications to the development of systems to assist fire management activities including prevention, preparedness, response and recovery. Such information based on the observation record is constrained to the few observation sites that have sufficiently long record, while climate model produced climate datasets tend to lack the spatial resolution required by fire agencies. A bias-corrected, downscaled reanalysis climatology over Victoria (VicClim) ameliorates these limitations.

Using the latest version of the VicClim gridded fire weather dataset, the spatial (~4km grid) and temporal (hourly) variability of fire weather for Victoria for 1972-2017 is explored, with McArthur's Forest Fire Danger Index (FFDI) representing fire weather. Various metrics are calculated: the 99th percentile of FFDI, probability of days with an FFDI over defined fire danger thresholds (High, Very High and Severe), and the decadal differences in these thresholds for all grid points. We also determine the Victorian averaged diurnal, seasonal and annual daily maximum FFDI, annual 90th percentile FFDI, and cumulative FFDI. The annual number of days with an FFDI above the fire danger thresholds are calculated, and finally we determine the variability of fire season length (FFDI days > 25) and changes to the start and end of the fire season.

It is shown that there is a significant positive relationship between fire activity (annual number of fires, total area burned) and annual accumulated FFDI. There is large spatial variability across Victoria in extreme (99th percentile) FFDI with the highest values in the north west and the lowest values in the Alpine region. The variability also differs across seasons with the biggest spatial contrasts in FFDI occurring in spring and summer. There is broad interdecadal variability in the 90th percentile FFDI averaged across Victoria through the study period, with a neutral period through the 1970s to the early 1980s, a negative anomaly from the mid 1980s to the end of the 1990s, and a positive anomaly from the early 2000s through to 2017, with a short- lived but strong negative anomaly in 2010-11. The broad interdecadal variability is also evident when daily maximum FFDI is separated by seasons for summer, autumn and spring but the upward trend in the most recent decades found in those seasons is not evident in the winter. Diurnal differences in trend and variability were observed with greater year-to-year variability and an upward trend since the early 2000s in summer 3pm and 9pm FFDI values but less variability and no upward trend in the summer 3am and 9am FFDI.

There are spatial variations in decadal changes in the number of days with an FFDI over 25 with some decades having one half of the state with above average number of days and the other half having below average number of days. Overall, the findings correspond with the Victoria averaged time series of below average number of days for each threshold in the 1990s and an above average number of days for each threshold in the 2000s. We find that the number of days with an FFDI over 25 for over 10% or more of the state each year (July to June) from 1972-73 to 2001-02 is on average 66 days. Since 2002-03 through to 2016-17 the average has increased to 94 days per year. There are only six fire seasons that have over 100 days with an FFDI>25 and these all occur between 2002-03 and 2016-17.

Finally, when the first and last day of the season with an FFDI of 25 is compared with a selected calendar date (1st Sep and 1st May, respectively) we find that from 1972-73 through to 2001-02 there were five occurrences of the fire season starting earlier, whereas since 2002-03 there have been 10 years that have had an earlier start. This trend to an earlier start to the fire season is also supported by an increase in the number of days with an FFDI over 25 in the transition month at the beginning of the season (September) being found. There is no increase evident in the number of days from the end date of the season or in the transition month at the end of the season (April).

The results from this study provide hitherto unavailable understanding of regional variability and trends in fire weather over Victoria for fire agency personnel to incorporate in the long term planning of resource allocation and landscape management.

Keywords: *Fire weather, trends, variability*

Wind-terrain effects on firebrand dynamics

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Abstract: Despite its importance in bushfire propagation, firebrand transport and the spotting process are still poorly understood, and there is no definitive model that can adequately emulate the spotting process in general. The dynamics of firebrands are difficult to predict due to the complex flow structure resulting from the interaction of a buoyant plume with a boundary layer wind field. Understanding the nature of this flow structure, especially for complex terrain, is essential for determining the likely path of firebrands and subsequent distributions of new spot fires and risk levels on structures downwind from the fire.

Although several prior computational modelling studies have carried out investigations of firebrand transport, the effect of the terrain has not previously been taken into account. It is well known that topography can significantly affect ember generation. For example, the enhanced intensity of a fire running up a steep slope can generate a large number of embers. More generally, terrain-modified flows and the strong turbulence associated with leeward slopes and flow around other prominent topographic features may have a pronounced effect on the transport of firebrands. Moreover, modes of dynamic fire propagation such as vorticity-driven lateral spread and eruptive fire spread in canyons involve a coupling between the fire, the terrain and the prevailing winds and so can affect the rate at which firebrands are produced as well as their subsequent transport.

In this study we use a coupled computational fluid dynamic (CFD) and Lagrangian particle approach to model the transport of firebrands. The model is applied to two different terrain scenarios to investigate the flow dynamics, firebrand trajectories and landing patterns resulting from the interaction with the terrain. The first scenario is a line of fire on the lee slope of a ridge burning perpendicular to an incident wind flow. The second scenario is a fire burning in a canyon aligned with the wind. The simulations indicate that the addition of terrain adds a further level of complexity to the flows generated by interaction between the wind and the fire. The terrain appears to modify the counter-rotating vortex pair in the plume structure. For the fire in the lee of the ridge line, the wind-terrain interaction resulted in a flattening and tilting of the counter-rotating vortex pair and enhanced regions of recirculation at the edges of the fire, which were conducive to lateral transport of embers. For the fire in the canyon, the channelling of the winds up the canyon resulted in the formation of a single jet-like vortex transporting firebrands upwards and over the top of the canyon. We hypothesise that this effect is caused by the shape and alignment of the canyon, which forces the vortex pair to merge into a single vortex.

Keywords: *Wildfire modelling, Firebrand, Computational Fluid Dynamics, Spark*

Incorporating firebrands and spot fires into vorticity-driven wildfire behaviour models

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Abstract: Complex modes of fire behaviour resulting from local coupling between the fire and the atmosphere are a significant challenge for rapid operational wildfire spread simulations. While three-dimensional fully coupled fire-atmosphere models are able to account for many types of fire behaviour, their computational demands are prohibitive in an operational context. Two-dimensional fire spread models have much lower computational overhead, but are generally not able to account for complex local coupling effects and cannot provide a three-dimensional flow structure suitable for modelling the transport of firebrands. In this paper we investigate extending two-dimensional fire spread simulations to model local coupling effects resulting from wind flow over a ridge that can result in a number of non-intuitive modes of fire behaviour. These include fire propagation opposite to the direction of the prevailing wind on the lee slope of ridges caused by re-circulation on the lee slope, called vorticity-driven lateral spread (VLS). Furthermore we develop extensions of these two-dimensional models to incorporate three-dimensional firebrand transport and show that enhanced downwind spot fire formation can result under certain VLS conditions.

The spread of fires under VLS conditions is driven by vortices in the ground plane. A model for the production and effects of these vortices was incorporated into computational simulations using a vector potential formu-lation in similar manner to a scalar 'pyrogenic potential' model, detailed in earlier studies. Firebrands were incorporated using a Lagrangian scheme to model transport through the atmosphere and a sub-scale model for spot fire creation and growth. The firebrand transport took factors such as drag, gravity and buoyancy into account. As effect of plume buoyancy on firebrands under real-world conditions for this scenario is currently unknown, the plume buoyancy was parameterised using a exponential decay model. The sensitivity of the decay parameter in this model was then examined in relation to the resulting spot fire distribution and area burnt. All simulations were carried out using Spark, a wildfire prediction framework.

The coupled VLS and firebrand transport simulations indicated that a higher value of decay parameter, rep-resenting a higher cooling rate of the plume, acted to enhance the lateral spread as firebrands were lofted for shorter times and were caught in the vortices at the edge of the lateral spread region. In contrast, a lower value of decay parameter, representing a lower cooling of the plume, resulted in widespread downwind spot fires and larger burnt areas. This appeared to be due to longer lofting times resulting in firebrands being transported further downwind and away from the vortices within the lateral spread region. The model appears, at least qualitatively, to match observed lateral spread and 'deep flaming' fire behaviour although many of the parame-ters in the model require further research and experimental calibration. Further development of the model may allow these complex modes of fire behaviour to be incorporated into rapid wildfire models for operational and risk assessment usage.

Keywords: *Firebrands, embers, spotting, wildfire simulation, dynamic fire propagation*

Stochastic model for the ROS in a heterogeneous environment

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Abstract: From a point source, landscape fires accelerate until they reach a quasi-equilibrium rate of spread. A fire is more easily suppressed by first-responders in its initial stages of development. As such, knowledge of the rate of acceleration of a fire from ignition can be valuable from a fire management perspective. However, the majority of studies in wildland fire science have been dedicated to development of models for the quasi-equilibrium rate of spread, attained after its acceleration phase. Comparatively little attention has been given to the development of models that specifically account for the growth phase of a fire's development.

The rate of acceleration depends on many factors including variations in ambient and induced wind speed and direction, variation in moisture content of the fuel, fuel stratification and slope variation. Present models of fire growth from a point ignition are expressed as deterministic algebraic equations, thereby neglecting variability. The numerous variables involved make predictions of rate of spread from a point source very difficult.

We propose the use of stochastic differential equations to investigate the growth of a fire in both a homogeneous and heterogeneous environment. This approach provides a more realistic portrayal of the time series data of fire growth. It also allows for better discrimination of the mechanisms driving the growth phase of fire spread.

Keywords: *Fire growth, fire acceleration, rate of spread, heterogeneous fuel, stochastic differential equation*

A cloud-based framework for sensitivity analysis of wildfire models

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Abstract: Natural hazard models, such as wildfire models, require a large number of input parameters. Consequently, the parameter estimation for such models become a high-dimensional, multi-modal and mostly non-linear problem. Sensitivity Analysis (SA) enables the selection of model parameters during calibration, helps to identify and treat uncertainties and provides crucial information about the use of the models. Recently, parametric SA has been used extensively to quantify the variability in the model outputs caused by variability in the input parameters for an optimized model. Such analyses can require the models to be run thousands or even millions of times to derive accurate sensitivity indices. Running these computationally intensive processes in a local computer or a small cluster can take several hours to days to complete.

With an almost unlimited capacity of scalable resources of compute, storage and network, Cloud Computing can provide an attractive alternative to High-Performance-Cluster (HPC) or supercomputers required for such computations. This feature of Cloud Computing must be coupled with different mechanisms to be able to conduct the sensitivity analyses of complex models in a convenient and timely manner. But, so far to authors' knowledge, an effective Cloud-based framework to accommodate the compute-intensive sensitivity analyses of disaster models has not been implemented.

In order to facilitate the sensitivity analysis of such models in a convenient, timely and efficient manner, we have implemented a Cloud-based service architecture (framework) as shown in Figure 1. The framework handles the computational complexity of the multiple model runs among the distributed Cloud resources and calculates the sensitivity indices for the input parameters to the model. In the service architecture, the user uploads a configuration file for running the models and enters the required inputs (Sample Size Argument, Number of input parameters, and SA method) into a web interface. The user can then access calculated SA indices from the web interface after all the simulations are completed and the indices have been calculated.

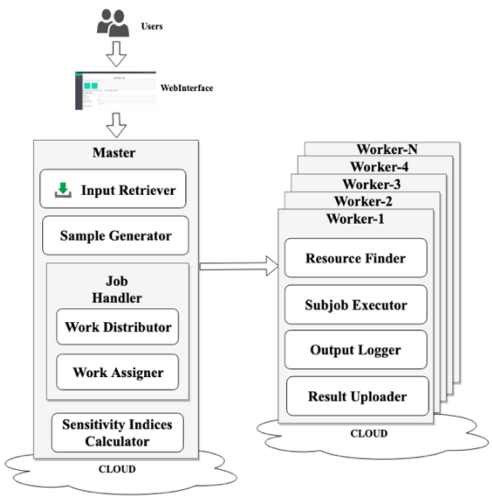

Figure 1. Proposed Cloud-based framework

We tested the Cloud service framework by calculating sensitivity indices for the input parameters of a wildfire propagation prediction model. Simulations were carried out over locations in Tasmania using Spark, a wildfire prediction tool. Fires were started at a set of points for different weather streams with temperature, relative humidity and wind speed as input parameters. Morris, Sobol and Fourier Amplitude Sensitivity Test (FAST) methods were used for the sensitivity analysis. Relative humidity was found to have the greatest effect on the variability of the area burnt, while temperature was found to have the lowest effect. The proposed framework allows sensitivity analyses of wildfire models to be efficiently carried out in a timely manner, utilizing the Cloud to reduce the time required for such analysis significantly. Such a capability could lead to a new operational tool for more informed risk management.

***Keywords**: Sensitivity analysis, wildfire modeling, uncertainty quantification, parameter uncertainty, Spark*

The flow over a forested hill

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Abstract: The atmospheric boundary layer flow dynamics over a vegetated hill, even though neutrally stratified, is far more complex comparing to the flow over flat ground. There is a need to study the dynamics of this flow in detail for the many environmental applications, such as forest management, wind energy monitoring for potential location of wind turbines, forest-atmosphere scalar exchange of pollutants, pollen, greenhouse gases, energy or momentum and forest fire propagation. There are many features of such a complex flow field with respect to the size of the hills and the leaf area densities of the forest. The rough and hilly surfaces can change the pressure field significantly that induces a distortion of the mean flow and generate specific turbulent eddies in the flow field. The flow on the upwind and on the summit of the hill are divided into inner and outer layer respectively based on the interaction time scale between eddies. In the inner layer, the turbulence reaches local equilibrium and the Reynolds stresses are larger and the time scale of interaction between eddies is higher compared to the outer layer. There are many interesting flow characteristics in the lee side of the hill: there is a wake region development with a reduced wind speed, a strong elevated shear layer and higher turbulence levels, and an intermittent separated or recirculation zone if the hill is sufficiently steep or the canopy is sufficiently dense (Dupont et al. 2008). Our motivation is to model the possibility of smoke and firebrand transport, spotfire ignition and fire intensity variations due to such recirculation in the lee side of the hill. Moreover, hills affect the local wind direction resulting in directional variation of the wind climate (Cook, 1990).

Large eddy simulation is performed in the Fire Dynamic Simulator (FDS) to study the features of atmospheric boundary layer flow over forested hills. To study the realistic features, a sufficiently large domain of 800 x 240 x 120 m in a nested yet computationally affordable grid resolution of 4 x 2 x 1 m is chosen with a periodic boundary condition in the streamwise and spanwise directions. The sparse and dense canopies are represented by a standard aerodymic model of drag that depends on leaf area density. A pressure driven flow is applied under neutrally stratified condition to explore the effect of hill and canopy induced perturbations including velocity speed-up, separation, attachment and recirculation.

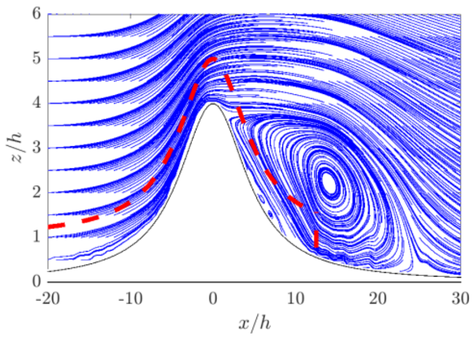

Figure 1. The recirculation formed in the lee side of a dense forested hill. The red dotted line is the 10 m height of canopy outline over the 40 m hill.

The flow fields in the upwind side, over the crest and lee side of the hill have changed significantly due to presence of the hill compared to the flat ground. The mean velocity is increased over the crest of the hill and continued downstream of the hill except in the lee side of the hill where a low velocity region is found. The mean pressure field is found lowest at the crest of the hill where the velocity reaches its highest and a layer of lower pressure zone is also found in the downstream region covering the lee side of the hill. The higher turbulent stresses are found in the lee side of the hill characterised by a reduced wind speed, low pressure and a recirculation zone as shown in Figure 1. It is found that the LAI densities can also contribute to the changes in turbulent shear stresses to some extent although the hill elevations are the dominating factor. The simulation results are qualitatively comparable with the existing literature. This study can be extended for parameterization of hill slope, hill size and inclusion of consecutive hills with the fire simulation.

Keywords: *Canopy, forested hill, LES, recirculation region*

Modelling the fire ecology of the Tasmanian Wilderness World Heritage Area

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Abstract: The Tasmanian Wilderness World Heritage Area (TWWHA) was listed as a World Heritage Area in 1982, satisfying seven of the ten World Heritage Area (WHA) criteria for Outstanding Universal Value, including all four natural and three cultural heritage criteria. Only one other WHA property out of more than 1000 worldwide satisfies as many criteria. Fire is an important part of the ecology of many parts of the TWWHA, while posing a severe threat to vegetation communities in other regions, and is intrinsic to the cultural heritage of the area. Natural fire plays a role in determining many vegetation communities, while anthropogenic burning over thousands of years has had a profound role in shaping the cultural landscape. Many ancient species of Gondwanan origin, such as native conifers and alpine cushion plants, contribute to the Outstanding Universal Values and are highly sensitive to fire. These iconic species are therefore at particular risk from fire in the face of a warming climate.

Management of fire within the TWWHA must balance the protection of assets of high strategic importance, including natural, cultural and economic values, with the maintenance of appropriate fire regimes for the landscape vegetation communities, species diversity and cultural heritage. Planned burning is the most powerful tool that land managers can utilise for increasing the likelihood of controlling bushfire within asset zones and maintaining a mosaic of fire ages in fire adapted vegetation communities to preserve natural values and the cultural landscape.

The Tasmanian Parks and Wildlife Service recently hosted a workshop that brought together Tasmanian ecologists from multiple organisations and backgrounds to collate their knowledge of vegetation dynamics into a model suitable for informing the development of a planned burning strategy for the TWWHA. The model describes the transitions between vegetation communities in response to fire or as the result of prolonged absence of fire. Individual transitions are characterised by fire frequency and intensity, and link together to form regression or succession pathways. Six pathway models were developed for different regions of Tasmania based on the broad geographical classifications of alpine, subalpine, and the four combinations of moist/dry regions with high/low soil fertility.

The model is applied at the landscape scale by use of high-resolution vegetation mapping combined with the observed fire history of the state. Simulation of the fire regime of the TWWHA is achieved through the application of high-resolution gridded weather data from either regional reanalysis or regional climate projections. Gridded weather data enable fuel moisture characteristics, lightning ignitions, and planned burning ignitions to be simulated, while other anthropogenic ignitions are simulated stochastically based on observed frequency and proximity to access points such as roads and walking tracks. Fire spread is explicitly simulated for each ignition using vegetation-specific fire behaviour models. A digital elevation model is applied to statistically downscale the gridded weather data and feeds into the fire behaviour calculations. Simulations enable variations of the planned burning strategy to be tested for their effectiveness at maintaining species diversity and the target fuel age mosaic, as well their effectiveness at reducing the frequency and intensity of unplanned fires within asset zones and across the landscape more broadly.

Keywords: *Fire ecology, bushfire, regional climate change*

Evolution of southeast Australian fire activity seasons

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Abstract: It is widely reported that climate change is impacting on wildfire risks in Australia. Fire seasons are seen to be starting earlier and finishing later. Climate modelling produces equivalent changes in fire weather. However national-scale datasets on fire activity are not widely available. A number of studies have used algorithm-generated "hotspots" from the pair of MODIS sensors carried on the TERRA and AQUA satellites for over 17 years. This dataset includes all types of fire – whether planned or not, and does not pick-up low intensity fire activity. It is also sensitive to cloud cover. Nevertheless, the MODIS hotspot dataset, covering 4.5 million records since July 2002, provides a coverage that is broadly complete and consistent within those constraints. Hotspots can be classified according to geographic location and time of year. McRae & Featherston (2015) used a technique of producing "wind roses" to show fire activity seasonality, showing relative occurrences by month. To do this hotspots were aggregated to one degree grid-cells.

In this paper hotspot "wind roses" are generated though aggregation to half-degree grid-cells over southeast Australia. To detect changes in fire activity patterns, the dataset is split into two epochs: Epoch 1 spans from July 2002 to June 2012, and Epoch 2 from July 2012 to June 2019. Impacts of climate change may be assessed through changes in key parameters of the pattern between the epochs. A number of grid-cells lack sufficient hotspots to form clear patterns. Others have fire activity through much of the year, and a seasonality pattern cannot be described. Change detection requires a defined pattern for both epochs.

The month of peak fire activity has a mix of no change, shifts to later months and shifts to earlier months. The geographic distribution of these is complex, although some regions can be identified as having uniform changes. The length of the fire activity period can be analysed in an equivalent manner. The length is identified where a single distinct peak of activity stands out from the other months. Maps of the length for both epochs were produced, as well as for the change in length. There is no evident geographic correlation between the two sets of results.

The Australian pyroCb register (McRae, *et al.*, 2015, di Virgilio, *et al.*, 2019) was assessed in conjunction with these patterns. PyroCbs are the most extreme and damaging form of fire behaviour, so any changes in their occurrence patterns are of concern. Given the limited dataset, there were still some regional patterns detected. It is noted that in some areas the month of peak fire activity in either Epoch is linked to extreme wildfire and pyroCb activity.

Without a clear filtering of wildfires or planned fires in the MODIS hotspot dataset it is not possible to assess trends in the timing of start or end of activity periods. Notwithstanding the constraints on the use of hotspots for this purposes, the results should form a benchmark against which to look for future changes and to validate climate model results.

Keywords: *Climate change, extreme wildfires, MODIS, hotspots, pyroCb*

A computational study on the implication of derived wind reduction factor in predicting fire rate of spread

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Abstract: Predicting the rate of spread (RoS) and intensity of bushfires is essential for emergency and disaster management organisations. Factors, such as localised topography, weather conditions, vegetation, and terrain have a varying range of influences on RoS, which makes the prediction highly complex. Currently, RoS predictions are achieved by implementing simplified operational models that have the useful attribute of providing results on time scales commensurate with the requirements of the emergency managers. Forest canopy and wind velocity play important roles in wildfire propagation. However, these roles vary due to the reduction of wind velocity during moving through the forest canopies of different leaf area density (LAD). Taking these two factors—wind velocity and LAD—into consideration, we derived a model (as shown in Figure 1a) of wind reduction factor (WRF) from synthetic data to model the varying wind velocity and hence, predicting the RoS.

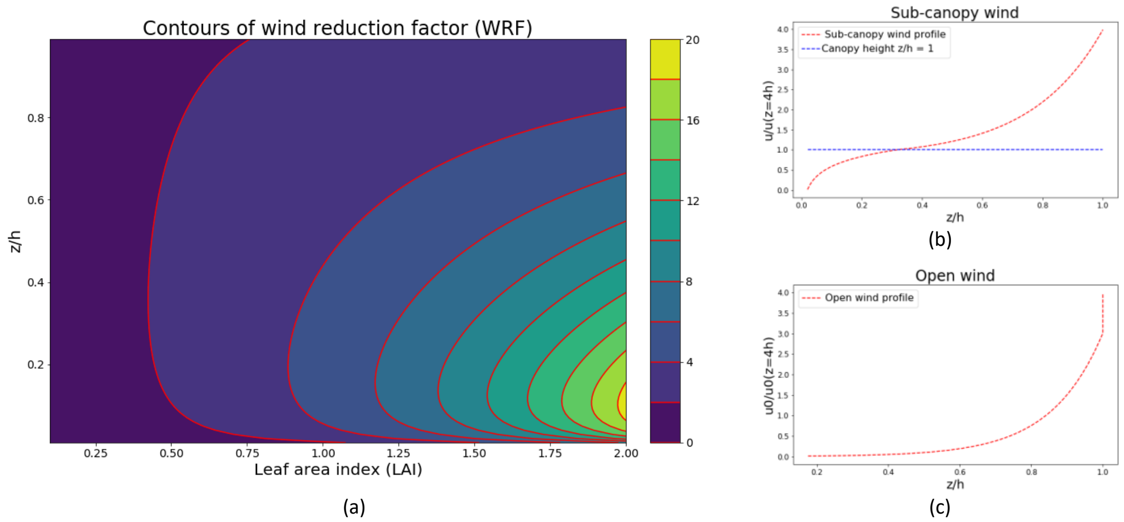

Figure 1. Profiles towards calculating wind reduction factor. (a) A map of wind reduction factor derived from synthetic data using Harnan-Finnigan Model; (b) and (c) are the profile of sub-canopy wind open wind respectively based on Finnigan model.

In some operational fire prediction models such as the McArthur model a pre-decided constant value of wind reduction factor is applied. For a dynamic fire passing through a canopy, the relationship between the wind speed and RoS appears more complicated than can be described by a constant wind reduction factor (Moon et al. 2016, Sutherland et al. 2018). Research into complicated fire canopy interactions is ongoing.

We implement this research into CSIRO's operational platform, Spark. The wind reduction factor is calculated within Spark running a C script by implementing Harman-Finnigan model (Harnan and Finnigan 2007) and a logarithmic model of the canopy-free wind speed. These models are based on leaf area index (LAI) which is relatively easily available from Landscape Data Visualiser[1]. Note that LAI only provides a dimensionless measure of vegetation per unit of ground area and uniform across the canopy height, which can be derived from LAD by integration. This work is the first step to implement dynamic wind reduction factor (based on fluid dynamics theory) in an operational model. In future, better models will be implemented based on homogeneous and then heterogeneous LADs along with involvement of fire dynamics.

[1] Landscape Data Visualiser: https://maps.tern.org.au/#/

Keywords: *Fire spread modelling, rate of spread, wind reduction factor, natural hazard, Spark framework*

Burn extent and severity mapping by spectral anomaly detection in the Landsat data cube

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Abstract: Mapping the extent and severity of bushfires is an important part of post-fire damage assessment and contributes to the fire history of a region. This information in turn is used in estimating the gradual increase in fuel load after the fire and hence is a key variable in anticipating future fire risk. Spectral indices, i.e., linear combinations of multi-spectral bands in remote sensing imagery, are conventionally used to determine burn extent and severity by comparing differences in imagery obtained pre- and post-fire events. For example, the Normalised Burn Ratio (NBR) exploits differences in the relative spectral response in shortwave and near-infrared wavebands to identify areas of burnt vegetation in satellite imagery. Well-known limitations of this differencing approach include its limited consistency and applicability over large areas, the requirement of *a priori* knowledge of where and when a fire occurred, and the need for imagery acquired within a reasonable time before and after the burn so that seasonal changes and recovery effects are minimal.

To address these challenges, we developed a combined burn extent and severity mapping approach that uses the full spectral information in time series of Landsat satellite observations available through the Digital Earth Australia archive. The method is primarily designed for perennial vegetation that does not burn frequently. The principle is to identify spectral anomalies in space and time, i.e., spectra that stand out significantly from the time series. The method quantifies the average spectral response of a pixel using the robust geometric median, which is relatively insensitive to residual atmospheric effects. Deviation of the spectral response from the geometric median is quantified through the cosine distance, a measure based on spectral similarity. Pixels with a distance greater than the equivalent of three standard deviations from the mean (i.e., statistical outliers) are identified as having changed. Subsequently, absolute and relative NBR and cosine distance changes are calculated to identify burns from other possible landcover changes. A subsequent region-growing step improves the classification by contracting pixels with below-threshold evidence of burning. In an optional post-processing step, corroborating data such as fire detections from thermal remote sensing (e.g., Geoscience Australia's Sentinel Hotspots fire detection system) and other ancillary data can be used to improve classification further.

We evaluated the method for several case studies in southern Australia through a comparison with independently derived burn extent maps provided by government agencies. The results show that the fully-automated algorithm developed produces classification results that are commensurate with conventional supervised image classification methods, but with the benefit of being repeatable and fully automated.

Keywords: *Burn mapping, spectral anomaly, Landsat, Digital Earth Australia, change detection*

Agent-based modelling of bushfire evacuations and the decision-making processes of evacuees

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Abstract: Evacuation is a key consideration of natural hazard scenarios—most notably bushfires in Australia—with the objective to minimise injury and loss of life. Entrapment is the devastating event where evacuees or emergency services personnel are overrun by an advancing fire front. Most deaths and serious injuries occur during entrapment events.

Modelling evacuation during a bushfire is complicated by the road network on which evacuees must travel, local geography, the position of the fire front, smoke, local weather and wind, the information available to evacuees, and, of particular note, social dynamics (such as described in Strahan et al. (2018) and Strahan et al. (2019)). Making the correct decisions, both at individual and strategic management levels will help avoid tragic outcomes such as the deaths that resulted from entrapments in the Black Saturday fires in Australia in 2009 or the Pedrogão Grande fires in Portugal, 2017.

We describe a new event-based agent-based model for simulating evacuations and the decision-making processes of evacuees throughout an evacuation scenario. The model is expected to inform tactical planning by emergency services agencies – for instance, to optimise the definitions of polygons for staged evacuation notices, to help guide community relations and education. Improvements to evacuation planning and community warnings may forestall the tragic consequences of large fire events.

The aim of the modelling process is to compare the evacuation times and safety outcomes for different archetypes of fire evacuees in various scenarios. Our model derives fire data from external models, simu-lations or observations. We can model evacuees' (incomplete) knowledge of aspects of the scenario, and and control evacuees' destinations by increasing the safety of evacuation centres. Results demonstrating the capability of the model in idealised scenarios are presented.

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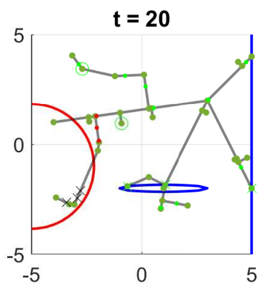

Figure 1. Illustration of agent based model simulation in progress. The red curve indicates a fire front. Blue curves indicate evacuation centres (regions of safety). The green network indicates a model road network. Markers indicate evacuee position and status: green circle, preparing to evacuate; green dot, orderly evacuation; green cross, safe; black cross, entrapped (dead); red dot, panicked evacuation.

Keywords: *Bushfire evacuation, agent-based modelling, social dynamics*

Evaluation of a simple rate of spread index applied to Canadian fuel types

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Abstract: The Canadian Fire Behaviour Prediction System (CFBPS) is used to predict fire behaviour across Canada and has been adapted for use in other parts of the world such as Europe and New Zealand. The CFBPS categorises fuels into fourteen different fuel types over five broad classes: coniferous, deciduous, mixedwood, slash and grass.

Rate of spread in each of the fuel types in the CFBPS is determined via calculation of the Initial Spread Index (ISI), which is defined as the product of two separate empirical functions of wind speed U and fuel moisture content m:

$$ISI = f(U)g(m),$$

where

$$f(U) = 0.208\,e^{0.05039U} \quad \text{and} \quad g(m) = \left(91.9\,e^{-0.1386m}\right)\left(1 + \frac{m^{5.31}}{4.93 \times 10^7}\right).$$

While wind speed is measured directly, fuel moisture content in the CFBPS is calculated using a sophisticated empirical modelling approach that accounts for both absorption and desorption processes, which are in turn modelled as functions of prior fuel moisture content, wind speed, relative humidity and air temperature. Given the overall complexity of the CFBPS rate of spread models, the question of model parsimony arises, and it is of interest to consider the possibility of more parsimonious approaches to modelling rate of spread in Canadian fuel types.

Indeed, recent research into the structure and parsimony of empirical fire spread models used in Australia has shown that for a number of different fuels types, the output of operational rate of spread models can be accurately emulated using a very simple approach. In particular, it has been shown that a single functional model, defined by two independent parameters, can accurately reproduce operational rate of spread predictions in fuels such as grass, shrubland, dry eucalypt forest, buttongrass and semi-arid mallee-heath.

It is therefore natural to wonder whether the simple approach to modelling rate of spread in Australian fuels might be more widely applicable to, for example, the fuel types in the CFBPS. In this paper we address this question by evaluating the performance of the simple modelling approach to Canadian grass fuels and to Ponderosa pine/Douglas-fir. These preliminary analyses demonstrate that the following simplified models are able to emulate predictions of the CFBPS for grass fuels (fuel type O-1) and Ponderosa pine/Douglas-fir (fuel type C-7) to within a reasonable degree of accuracy:

$$S^*_{O1} = 20.74\left(\frac{\max(1,U)}{FMI + 1.84}\right)^{0.74}, \quad S^*_{C7} = 3.064\left(\frac{\max(1,U)}{FMI + 5.39}\right)^{1.98}.$$

An alternate quadratic model for the C-7 fuel type is also discussed, and some general discussion of how the simple modelling approach can be used to provide guidance on fire behaviour in more general fuel types is provided.

Keywords: *Rate of spread, grassland, Ponderosa pine, Douglas-fir, model parsimony, wind, fuel moisture content*

Using Windninja data into Fire Dynamics Simulator for faster fire simulations

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Abstract: Wildland fires occur naturally in several parts of Australia and around the world and result in loss of life and property. The need to control and manage such fires opens up an extensive domain for research. This has lead to the development of several numerical models to simulate these fires and provide mitigation plans. Physics-based models act as a strong research tool to study this fire behaviour. Fire Dynamics Simulator(FDS) which is a physics-based model, has been used in the current work to model the fire. The major drawback of physics-based models is that they have high computation cost to model and simulate fires as they use very small grid-size (in order of few centimetres to millimetres) to capture the relevant components of fire. This paper introduces a new inlet-outlet interface method named PenaBlending Method which has been added to FDS. This method allows it to use terrain-modified wind data from reduced and faster wind models like Windninja and carry out fire simulations. This results in reduced computation cost.

The fire spread strongly depends on the wind speed and therefore generating a statistically stable wind profile is a pre-requisite for starting any fire simulation. The existing wind generation methods of FDS requires a considerable amount of simulation time to reach the required wind profile for starting fire. Currently, the standard release of FDS does not have the capability to use wind data generated from any external methods. The PenaBlending method, which we have introduced in FDS 6.6.0 will allow the users to use any external data, generated by any external methods to be used as inlet and outlet condition to model fire. Windninja is a simple wind model which can simulate terrain and temperature modified wind at lesser than 50 m scales, which can be beneficial for fire management. The conservation of mass model of Windninja has a very low computation cost (in the range of few seconds for approximately 1.17km $\times$1.17km domain). We have used wind data generated from Windninja as an inlet and outlet condition in FDS using the PenaBlending method to perform fire simulation and hence reducing the wind development time in FDS. The schematic of the methodology has been shown in Figure 1.

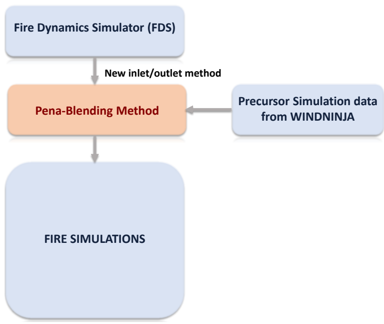

Figure 1. Schematic representation of the methodology

The FDS domain that is considered in the current study has a dimension of 130m $\times$ 40m $\times$80m having a uniform flat surface. The burning area id resolved with a mesh with grid size 0.25m$\times$0.25$\times$0.25m. The modelling domain considered for Windninja is a Digital Elevation Model (DEM) of a flatland near northern boundary of Melbourne, Australia. The Windninja domain has an area of 1.17km $\times$1.17km, with an uniform grid of 23m along x and y direction and stretched grid along z direction. Due to the mismatch in the domain sizes, a portion of the Windninja data has been cut out and has been interpolated to the required grid size as that of the FDS domain. The wind data from Windninja are introduced at the inlet and outlet along the stream-wise direction. It has been observed that using Windninja wind data, a statistically stable wind profile is obtained as quickly as $\sim 50s$ from the start of the simulation as opposed to $\sim 400s - 500s$ using the existing wind generation method in FDS, to start a fire. It is envisaged that the Windninja data or any other external data along with the PenaBlending method can be used to model more complex structures and simulate fire over them with a much reduced computation time.

Keywords: *Fire Dynamics Simulator(FDS), Computational Fluid Dynamics, PenaBlending Method, wind*

Probabilistic modelling of bushfire rate of spread from line scan observations

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Abstract: Accurate predictions of bushfire spread are important for understanding the time and location of bushfire impact, allowing for community warnings to be issued and fire crews to be deployed effectively. Fire spread models are currently used within fire agencies in SE Australia for operational fire spread predictions. These predictions are important as decision support tools. However, their utility can be undermined if inaccurate predictions are produced. Overpredictions of fire spread rates could lead to unnecessary evacuations, resulting in major disruptions to communities. However, more dangerous are under-predictions of fire spread rates, as this means communities could be impacted by fire much sooner than expected. Cruz and Alexander (2013) collated many studies of predicted spread vs observed spread for many different fire spread models and found under-prediction bias in 75 % of the datasets tested.

A major problem with currently available spread models is that they were often developed using observations from experimental fires ignited during relatively mild fire weather conditions. Predictions for more extreme fire weather conditions are achieved through extrapolation, or by incorporating a limited number of observations from more extreme fires. Historically, it has been difficult capture data of more extreme fires for model training, as experiments in extreme weather are not possible due to the danger involved. Observations of uncontrolled bushfires in more extreme conditions have been difficult to collect due to the danger involved, lack of suitable equipment available and relatively short time periods when fires are spreading at their maximum rates (e.g. over a single afternoon). However, in the past 10 to 15 years in NSW and Victoria, fire agencies have been routinely collecting multispectral line scan images from aircraft flown over actively burning bushfires. The purpose of this data collection is to identify fire extent and produce maps for operational purposes. However, line scans are also the best data captured of actively burning bushfires. While often only single line scans are captured, for some bushfires multiple sequential line scans are captured. This allows for fire progression isochrones to be created in a GIS and rate of spread to be calculated. The data can then be overlayed with environmental data on fuel, topography and weather, giving the opportunity for bushfire spread to be modelled. Satellite platforms such as MODIS also provide similar (although much coarser resolution) data that can be used for mapping spread of very large bushfires.

In our study to date, a large accurate dataset of bushfire spread observations in SE Australia has been created. 150 fires from a range of fuel, weather and topographic conditions have been mapped from the line scan data (and some MODIS data). This has created 325 individual rate of spread observations for analysis (some fires have multiple observations). Measured rates of spread range between 0.02 kmh^{-1} and 6.2 kmh^{-1}, with a mean of 1.2 kmh^{-1}. Rate of increase in fire area ranged between 0.4 hectares per hour and 8823 hectares per hour, with a mean of 441 HA per hour.

We will use this data and Bayesian statistics approach to investigate the possibility of producing a probabilistic bushfire rate of spread model. While this is in the initial stages, this Bayesian approach is promising, as it allows for the incorporation of uncertainty in predictors. As it is often difficult to obtain accurate data during an actual bushfire, such as local fuel conditions and weather conditions (including local weather variation), the probabilistic approach could allow for more insightful predictions to be produced.

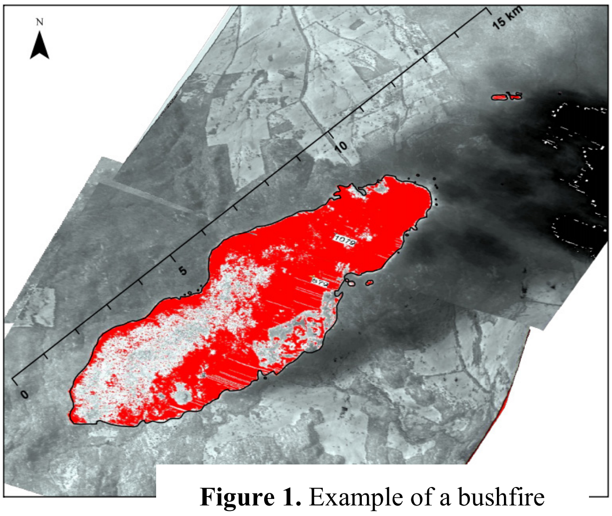

Figure 1. Example of a bushfire infrared line scan

Keywords: *Bushfire, rate of spread, probabilistic, line scans*

Coupling litter and soil moisture models to forecast surface fuel moisture content

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Abstract: The fuel moisture content (FMC) of the litter layer (i.e., surface fuel) is a critical factor determining fire ignition and spread, and is an important input for most fire danger and fire behaviour prediction methods. Several models have been developed to forecast litter FMC. Those models range from empirical regression functions against weather variables to process-based models with water and energy conservation equations. Soil moisture has been shown to influence dead FMC, but few models explicitly consider the role of soil moisture dynamics in determining litter FMC. This research aimed to evaluate how soil moisture content affects litter FMC forecasts by coupling separate models of litter and soil moisture dynamics. A process-based model (Koba; Matthews, 2006) that simulates litter fuel radiation, energy and moisture fluxes was coupled to a grid-distributed hydrological model, the Australian Water Resources Assessment system Landscape model (AWRA-L) used by the Bureau of Meteorology (BoM) to estimate soil moisture and other hydrological variables. The models were coupled by considering the vapour exchange between soil and litter (Figure 1). The coupled models were tested at five sites in Victoria where litter FMC observations were made using a network of automated fuel stick sensors operated by the Victorian Department of Environment, Land, Water and Planning. It is noted that the fuel stick moisture content does not necessarily always equate to the litter FMC. Two versions of the Koba model were compared against FMC observations for 2014–2015; an uncoupled version, and a version where the vapour flux between soil and litter was included as a boundary condition. The coupling was one-way only, i.e., the Koba fluxes did not change the AWRA-L simulations. All input data were available at daily and 0.05° resolution: minimum and maximum temperature, vapour pressure, precipitation, incoming short-wave radiation, wind speed and topsoil moisture content. Results show that the coupled model produces slightly better simulations than the uncoupled model, especially for the bottom litter layer in contact with the topsoil. However, the improvement in estimates was slight in most cases, which is likely to be at least partly due to the coarse spatial resolution of input data and the lack of spatial data to constrain soil and litter parameters. Improving the estimation accuracy of the coupled method is the focus of ongoing research. It is being addressed through a series of controlled factorial field experiments with different experimental treatments (i.e., with and without direct contact between soil and litter, and at a dry exposed and a moister, sheltered location) to better understand and quantify the processes involved in coupling litter and soil moisture dynamics.

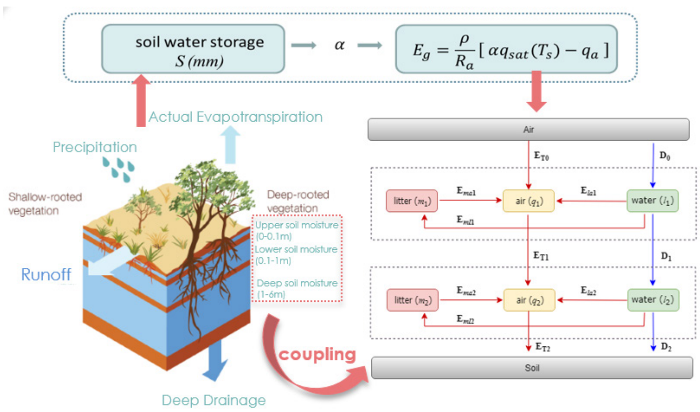

Figure 1. Illustration of (left) the coupled AWRA-L soil hydrology and (right) the Koba litter moisture model. Each Koba layer includes litter, water and air and the water content of them are m_1, l_1 and q_1 respectively. Red arrows represent vapor flux between materials (vapor flux between litter and air E_{ma}, vapor flux between water and air E_{ml} and turbulent vapor flux E_T) and blue arrows represent liquid water drainage (D).

Main Citations: [1] Matthews, S., 2006. A process-based model of fine fuel moisture. *International Journal of Wildland Fire*, 15(2), pp.155-168.

Keywords: *Fuel moisture content, forecast, coupling model, soil moisture*

Evaluating the ability of a regional climate model ensemble to simulate temperature extremes

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Abstract: Climate information at appropriate spatial and temporal scales is critical for supporting evidence-based decision making. Regional climate models, by translating coarser resolution global climate model data into a more locally relevant form, aim to address this need. This is true for sectors such as the energy industry where climate information is required at scales much finer than what global climate models output (average of ~200 km). And while planning for the increasing frequency and magnitude of temperature extremes will help lessen the consequences of these events, such planning requires these phenomena to be well represented in downscaled data.

The climate of south-east Australia is well described by range of downscaled climate data. The most comprehensive are the results of the New South Wales and Australian Capital Territory Regional Climate Modelling (NARCliM) project (Evans et al., 2014) which produced a 12-member regional climate ensemble by dynamically downscaling 4 global climate models with 3 regional climate models at two spatial resolutions, 50 km and 10 km. The NARCliM ensemble simulates the mean climate of south-east Australia well but its ability to simulate temperature extremes is less well-known, though is not unstudied (Gross et al., 2017).

Here we assess the ability of the NARCliM ensemble to simulate temperature extremes to help judge the veracity of its projections. This will help answer the question: can the projections of extreme heat by the NARCliM ensemble allow us to adequately plan for a warmed future in south-east Australia?

To answer this question, we look at the suite of data produced by the NARCliM product and focus our analyses on a rapidly expanding region which is already one of Australia's most populous areas: Greater Sydney. NARCliM produced output at two spatial resolutions (50 km and 10 km) and bias-corrected its initial outputs. This provided the opportunity to assess whether increased spatial resolution or the bias-correction method improved model performance. To complement this analysis, and to quantify the 'value-add' of the downscaling exercise, the 4 host global climate models are also examined.

To assess model performance, we use a range of methods that have been replicated in similar evaluations (Rimi et al., 2019). This includes 1) computing temperatures extremes indices temperature to examine 'moderate' extremes and 2) estimating return periods to examine the most 'extreme' extremes. The Australian Water Availability Project (AWAP) observational gridded dataset was used for the evaluation. As it is an interpolated product, to quantify the impacts of the gridding process on the tails of the distribution (typically interpolation dampens extremes), AWAP and a station-based observational dataset (ACORN-SAT) are also compared. Our methods are not region specific and could be applied to any climate model.

Overall, our results find that temperature extremes are well represented in the NARCliM ensemble.

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Keywords: *Temperature extremes, dynamical downscaling, model evaluation*

Understanding past and future changes to global flood hazard: Comparison of global hydrological models with streamflow observations

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Abstract: This presentation provides a comparison between an extensive global database of annual maximum streamflow comprising 3,666 gauging stations (GSIM), and six global hydrology models. The objectives of this comparison are to understand the extent to which the models simulate historical changes to the annual maximum flow events over the period from 1971-2005, and assess the implications on future change. Four indices of change are considered: average trend magnitude, standard deviation of the trend magnitude, the fraction of stations showing statistically significant trends, and the spatial pattern of change.

Results show that, when compared to the observations, models forced by reanalysis data generally exhibited a higher average rate of change, lower standard deviation, and similar percentage of locations with statistically significant trends. Moreover, the models showed moderate capacity to simulate spatial patterns of change. When comparing these results with results from models forced by GCM hindcasts over the same historical period, a number of important differences were observed particularly to the regional patterns, showing a potentially significant role of natural climate variability in explaining historical trends.

There is the potential for global assessments of flood hazard using observational data products such as GSIM to be heavily biased towards well-gauged regions such as North America, Western Europe and several other regions around the world. To evaluate this issue, global trends from the hydrological models were compared when averaging across all grid cells with averaging only over the grid points that contained streamflow gauges. This analysis highlighted the potential for substantial underestimation of the magnitude of global trends, with the hydrological models identifying that the regions with the greatest rates of increasing trends often corresponded to some of the most poorly gauged regions around the world.

Lastly, up to 35% of grid cells globally show statistically significant trends (increases and decreases) for RCP 6.0 over the 21st century. This suggests that regardless of the magnitude of the global average trend, there are likely to be significant regional features, with the potential of substantial change across much of the global land surface.

Keywords: *Flood hazard, GSIM, global hydrological models*

Future changes in storm related indices for Australia

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Abstract: Four indices, namely, the convective available potential energy (CAPE), the convective inhibition (CIN), the lifted condensation level (LCL) and the level of free convection (LFC) are widely used to describe the conditionally unstable processes. Any changes in these indices will have potential impact on convective processes which is directly related to diverse types of weather systems such as thunder storms.

In this study, we used the modelling outputs from the NSW/ACT regional climate modelling (NARCliM) project to calculate CAPE, CIN, LCL and LFC. In NARCliM, 4 selected global climate models (GCMs) were used to drive 3 selected regional climate models (RCMs) to form 12 GCM/RCM combinations. Each GCM/RCM combination was run for three 20-year periods (1990-2009, 2020-2039, and 2060-2079). The Australasia domain (50 km resolution) covers the whole of Australia, and 3 hourly modelling outputs allow us to analyze diurnal variation of future changes. We investigated future changes in mean annual and seasonal values of the four indices and their diurnal variations. Differences between same GCM driven simulations (each with 3 RCM simulations) and difference between same RCM used simulations (each with four GCM simulations) were analyzed. Results for selected CMIP5 GCM downscaled simulations were also included for comparison.

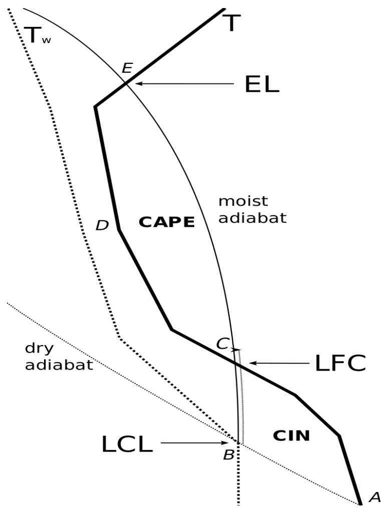

Figure 1. The conceptual diagram showing an air parcel path when raised along B-C-E compared to the surrounding air mass Temperature (T) and humidity (Tw)

The results show substantial changes in 4 indices in future for Australia and clear differences between Southern and Northern Australia. CAPE is projected to increase more than CIN, however, LCL and LFC are projected to decrease for Northern Australia, which indicates that the atmosphere will be more conditionally unstable. In contrast, CAPE is projected to increase a little, but CIN, LCL and LFC are projected to increase considerably in Southern Australia, which suggests that the atmosphere will become less conditionally unstable in the future. Future changes in CAPE, CIN, LCL and LFC have clearly seasonal and diurnal variations, however, only changes in CAPE show larger seasonal and diurnal variation for Northern Australia than Southern Australia. Future changes for different simulations are vary substantially. The difference in future changes between same GCM driven simulations are generally larger than those between same RCM used simulations.

Keywords: *CAPE, CIN, LFC, LCL, NARCliM, ensemble mean, future projection*

Comparison and application study on conditional stability and convective stability

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Abstract: Thermal instability is the precondition for the occurrence of atmospheric convection, and it is also the inherent essence and driving force for the occurrence and development of convective systems. The typical indices for measuring atmospheric thermal stability are divided into two categories, one is the conditional stability index and the other is the convective stability index. Conditional stability is the most basic thermal stability parameter, which directly characterizes the environmental buoyancy of the lifted air parcel. The most representative indices are the Showalter Index (SI) and the Lifted Index (LI). The convective stability index is a measure of the change of conditional stability for the layer after the overall uplift. In practice, the equivalent potential temperature difference between the middle layer (500 hPa) and the lower layer (850 hPa) is commonly used.

In this study, three radiosonde stations in Beijing, Nanjing and Zhangzhou are selected to represent North, Central and South China respectively. Using 10 years of summer sounding data, statistical analysis is carried out on stability of the three stations. The results show that:

- If SI<0 is taken as indicator of conditional instability, and the equivalent potential temperature difference between 500hap and 850 hPa less than zero as convective instability, the climatic probability of conditional instability in Beijing, Nanjing and Zhangzhou is 19.4%, 27.9%, 53.9%, respectively. While the climatic probability of convective instability is 57.2%, 55.4%, 81.6% individually.
- The probability of convective instability is higher in summer for the three stations, and the convective instability strength should be analyzed when judging convective instability. The difference between conditional stability and convective stability in North China is the largest, usually conditionally stable, but convectively unstable.

As it is difficult for SI to show the diurnal variation of stability and for LI to overestimate diurnal variation, a universal conditional stability index “Total Mean value of Buoyancy Temperature Difference” (TMBTD) is designed. Taking actual soundings or numerical model outputs, the buoyancy temperature difference from each lower level to all upper levels below 500 hPa are calculated, and averaged to represent the general trend of conditional stability of all lower possible disturbed air parcels lifting to higher levels up to 500 hPa. The study applies the simulated output of the finer numerical model and assesses the characteristics of the TMBTD. The results show that:

- The unstable mean value of TMBTD is ahead of the occurrence of convective precipitation and has a delayed negative correlation with precipitation. The numerical simulation of a severe storm process shows that the strong average condition of the buoyancy temperature difference precedes by 140-minute large-scale heavy rain.
- The TMBTD has obvious daily variation characteristics and can objectively reflect the weather process information in the atmosphere. From the perspective of spatial distribution, the TMBTD also has a good correspondence with the precipitation area and precipitation amount in the later 6 hours.

The graphical representation clearly shows the difference between the two types of stability indices in terms of concept and physical nature, which will help users to better understand them. A modelling case study of severe storm event shows that the process of gradual changes of stability from convective instability to conditional instability.

Keywords: *Conditional stability, convective stability, Total Mean value of Buoyancy Temperature Difference (TMBTD), convective precipitation*

Revisiting the Australian/New Zealand Standard for Wind Actions (AS/NZS 1170.2:2011): Do current wind standards sufficiently capture local wind climates?

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Abstract: The Australian/New Zealand Standard for Wind Actions (AS/NZS 1170.2:2011) provides advice on wind direction multipliers (M_d), regional wind speeds (V_R), and other relevant considerations to assist in designing and building structures. AS/NZS 1170.2:2011 identify eight individual wind regions for Australia, with regionally specific M_d and V_R values which can be applied to calculate the directional wind speed. Given the vast expanse of Australia and various wind hazards in both cyclonic and non-cyclonic wind areas, it is essential to accurately quantify current and future wind risk that is representative of the local wind climate. As such, this study compares the M_d component of the AS/NZS 1170.2:2011 standards for four wind regions (A1, A4, B and C), with observed wind data (4 stations per wind region) – see Figure 1 for more details. Findings suggest that the wind regions analysed do not adequately represent the wind climates of the stations considered within each wind region. For example, while AS/NZS 1170.2:2011 assume that the same directional wind multipliers should apply for Perth and Adelaide, we show that the prevailing direction of the strongest wind gusts ($\geq$ 99.9th percentile) varies considerably between stations. Using station data to model M_d suggests that AS/NZS 1170.2:2011 can underestimate wind risk for region A1 (70% of cases) and overestimate between 62-77% of cases for regions A4, B and C. These results highlight some inadequacies with AS/NZS 1170.2:2011 and suggests more regionally-specific wind direction multipliers that are more indicative of local wind climates are required.

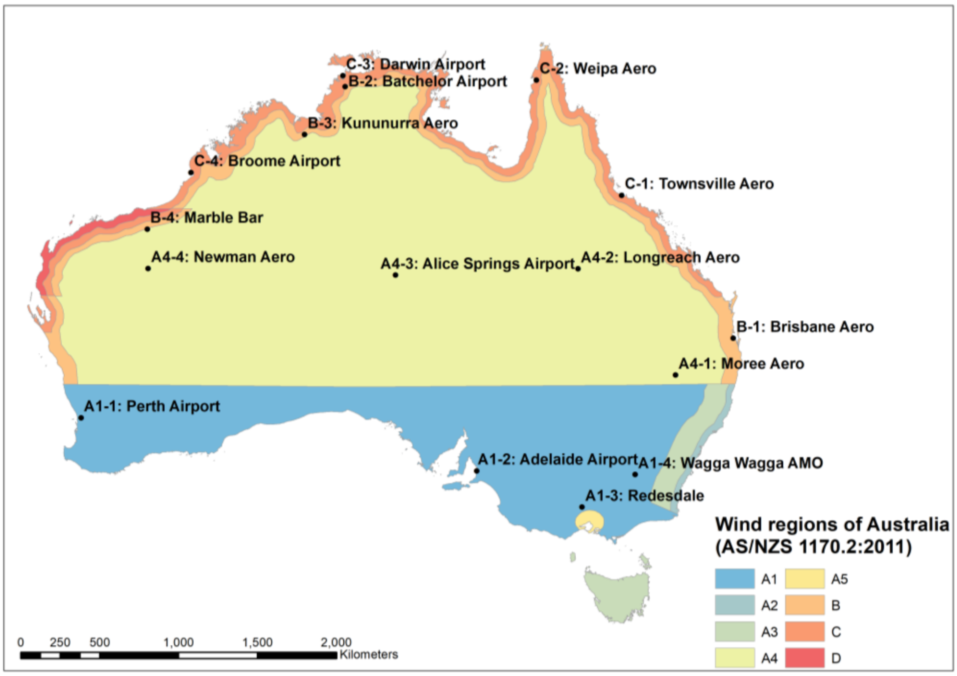

Figure 1. Location of Bureau of Meteorology (BOM) weather stations used for analysis from wind regions A1, A4, B and C.

Keywords: *Wind hazards, wind extremes, AS/NZS 1170.2:2011, Building Code of Australia (BCA)*

INVITED PAPER

EXTENDED ABSTRACT ONLY

Hydrological modelling as the alternative to flood frequency analysis in a changing climate

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Abstract: Recent flood hazards and the damage caused mainly by unprepared infrastructure in the last two decades in different regions of Russia suggest that the flood frequency analysis of even long-term historical data may mislead design engineers to significantly underestimate the probability and magnitude of flash floods (Makarieva et al., 2019a, b). This is due to climate change which not only breaks the uniformity of streamflow series but in some cases revokes the legacy and therefore usefulness of those historical data. There are many evidences of observed precipitation regime transformations which directly contribute to the formation of dangerous hydrological phenomena such as flash floods (Chernokulsky et al., 2019; Makarieva et al., 2019c).

Recent examples of such situations could be observed in the summer of 2019 when historical floods hit the Irkutsk region of Russia with lost lives and total estimated damage more than 0.5 billion USD. The town of Tulun at the Iya River (about 40 000 people) was heavily affected by floods in June and August. In 2010 the dam was constructed in Tulun to protect the town from floods. The dam constructed was too small and overspilled twice in 2019, as the flood frequency analysis conducted for the dam project suggested that the hazard flood of 1984 was historical and could not be repeated in the next 50 years. Interestingly, the analysis of streamflow data for the Iya River suggested that there are statistically significant decreasing trends of maximum discharges from June to August of 24-38% for the whole continuous period of observations from 1933 to 2017.

In this study we used the *Hydrograph* model (Vinogradov et al., 2011) to estimate flood frequency curves for ungauged rivers in several flood-prone regions of Russia based on hydrological modelling and compared the results to standard flood-frequency analysis based on the data of river-analogues with long-term streamflow observations. The results have shown that the standard flood frequency analysis may significantly underestimate the recurrence and the magnitude of flash floods. The details of the study will be presented.

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Keywords: *Flood hazards, climate change, flood frequency analysis, Hydrograph model*

Multi-hazard risk assessment and insurance pricing based on adapted local sample capture – a case study on rural housing in Zhejiang Province, China

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Abstract: The occurrence and loss of natural disasters are affected by the regional disaster-prone environment. Consequently, natural disaster losses and risks exhibit obvious regional differences. In multi-hazard risk assessment and insurance pricing based on stochastic event simulation, probability distributions are derived from spatial samples which contains critical information about the inherent regional differences of losses and risks. Consequently, sample selection critically influences the final results.

Based on the basic principles of geospatial proximity and similarity, this paper develops a multi-hazard risk assessment and insurance pricing method based on the spatial density of sample events and adaptive local sample capture and event simulation. It employed the general framework of collective risk theory for multi-hazard risk assessment and insurance pricing, by deriving the compound distribution of event frequency (occurrence) and severity (loss size) using stochastic simulation. In multi-hazard event occurrence simulation, it used the spatial kernel density analysis based on local adaptive sample selection instead of fitting a global frequency distribution. In multi-hazard event loss simulation, it used local sample fitting and random variable simulation based on semi-variogram instead of a global loss distribution.

The method was applied to rural house insurance indemnity records in Zhejiang Province, China during 2009-2018, which were results of multi-hazard damage in nature. The results show that the spatial samples selected 0.6 degrees as the local optimal capture radius, which is much smaller than the average range of county-level administrative units in Zhejiang Province. Compared with the results of dividing samples using administrative boundaries, our results based on spatially adaptive local sample capture were much closer to the spatial pattern of empirical results, and also offered results with higher spatial resolution. Our method may have wider application in the future implementation of multi-hazard risk assessment and insurance pricing methods.

Acknowledgement: Financial support from National Key R&D Program of China with grant No. “2018YFC1508903” is highly appreciated.

Keywords: *Multi-hazard risk assessment, Adaptive local sample capture, collective risk theory, Kernel density estimation, semivariogram analysis*

EXTENDED ABSTRACT ONLY

Simulation-Optimisation for coastal flood risk management

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Abstract: This study demonstrates the use of a simulation-optimisation approach for exploring the effectiveness of development exclusion zones along the Greater Adelaide Coastline to mitigate coastal flooding. Development exclusion zones are areas of land where government policy prevents the construction of new buildings and other infrastructure which may have otherwise been undertaken to enable certain economic or social activities. In the flooding context, excluding development in flood prone regions is often beneficial for preventing future flood losses. Simulation-optimisation refers to the integration of optimisation techniques into a simulation-based analysis, and is beneficial for managing coastal flooding, because:

1. Optimisation is able to screen through and identify mitigation options that perform best across a number of decision criteria. This is important, as there is a very large number of zones from which development could be excluded, that could be combined in an extremely large number of ways. The use of optimisaton enables the identification of a shortlist of options for further consideration.

2. Simulation is able to quantify the effectiveness of management options over long-term planning horizons. This is important, for management options may have long lead-in-times, and/or may have long lifetimes. Hence, they are not readily changed, and need to be effective over a broad range of plausible future conditions, including changes in population, increased economic development and climate change. Simulation is needed to appropriately represent how these future changes will impact decision criteria. For example, land use change needs to be simulated due to the bottom-up and dynamic nature of some critical processes that result in land use transition.

3. The approach emphasizes a holistic assessment, wherein an integrated assessment model (IAM) is used to simulate the effect of proposed management options across a number of criteria, therefore allowing practitioners to explore the trade-offs between risk reduction with other community goals, including environmental, social and economic outcomes.

Results show that if left unmitigated, coastal risk is likely to increase by around 10% over the next three decades, based on sea level rise estimates from the Climate Change in Australia project and modelled changes in land use consistent with Australian Bureau of Statistics projections. In evaluating the effectiveness of exclusion zones, the multiobjective approach characterized the complete tradeoff between the amount of area excluded and the associated reduction in risk. For example, zonal exclusion policies could almost entirely prevent the growth of risk by excluding further development from 7000 Ha of land. However, the growth in risk could also be limited to only a 3% increase, through excluding development from only 1500 Ha, which may be more palatable for city planners and acceptable to the community.

Through application to a case study, this study shows how simulation-optimisation holds much promise for increasing the effectiveness and efficiency by which IAMs can be applied to natural hazard risk management. The role of the optimisation was seen not to be prescriptive, but to enable better exploration of risk management options. The combination of optimization and IAMs is therefore able to provide rich information on the effectiveness of management portfolios, by which better risk management plans can be formed. This richness of information is important as greater demands are being placed on planners to effectively manage natural hazard risk. To realise this need, additional mitigation options and objectives are discussed to further develop the simulation-optimization problem addressed in this study.

Keywords: *Flood risk management, Integrated assessment modelling, Optimisation, Genetic algorithms, land use simulation*

The role of forcing anomalies and climate shifts in seasonal forecasts

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Abstract: We devise a new method for determining the effects of model forcing anomalies and climate shifts on seasonal predictions. The role of model bias, due to anomalous forcings, and climate shift on forecast skill is studied for coupled ocean-atmosphere general circulation models (CGCMs) during different phases of the El Niño Southern Oscillation (ENSO) cycle. Biases due to anomalies or errors in the model forcing functions in simulations produce changes in the attractor of the thermo-dynamical system and shifts in the consequent climate state. We examine how such biases and climate shifts affect seasonal predictions.

We employ an efficient intermediate complexity model with established forecast skill in a standard configuration and analyse seasonal predictability during a 20-year period of intense El Niño and La Niña events starting in January 1980 and ending December 2000. Firstly, we use reanalysed data from the observations to perform seasonal forecasts using our intermediate model with the optimised forcings for the standard configuration. Forecasts for one year are produced starting each month of the analysis period. The same initial conditions are then used by the intermediate complexity model, together with changed forcings that closely reproduce climates from selected complex CGCMs, to produce two additional control forecasts. We then determine the effects of the anomalous CGCM forcings, or model biases, and climate shifts, by comparing how well the forecasts with these configurations perform in situations of developing and large amplitude El Niños and La Niñas. We calculate the forecast error of the 50m ocean temperatures in the Pacific Ocean region and show the model's variability in forecast error growth during the annual cycle. Larger amplitudes of error are seen during the development of El Niño events in all cases, with the seasonal predictions with CGCM determined forcings showing evidence of drift towards the shifted model climate with overall increased forecast error.

Keywords: *Seasonal forecasts, model bias, model climate, El Niño Southern Oscillation*

Seasonal variation in the extreme precipitation-temperature scaling relationship

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Abstract: Extreme precipitation events are widely expected to intensify in a warmer climate based on the increase of saturation water vapour pressure with increasing temperature, as governed by the Clausius-Clapeyron (CC) relation. Due to the difficulty in finding long-term trends in observational data and the current limited capability of model simulations, variations of precipitation intensity with temperature, termed scaling, have received a lot of attention due to their ability to exploit higher confidence modelled temperature projections. However, scaling rates between precipitation intensities and temperature have been found to vary significantly across the globe. Negative scaling relationships have been found in many regions characterized by warmer climates, including the north coast of Australia while scaling rates well in excess of that predicted by the CC relation (7%/°C), so-called super CC scaling, have been found in the same major climate zone along the north-east coast of Australia.

We propose a seasonal analysis of extreme precipitation-temperature sensitivities to allow for a more detailed investigation of the responsible mechanisms. Sub-daily precipitation and temperature data for 350 synoptic stations across Australia are analysed. Two airport stations, representative of opposing scaling regimes along the northern coastline, are subjected to greater scrutiny: Darwin, where negative scaling has been found; and Cairns, where super CC scaling occurs. Seasonal distinguishing of event pairs is based on a summer season (Oct-Apr), winter season (May-Sep), as well as an annual period for control.

Results indicate that seasonal differentiation for Cairns can result in the calculation of two lower seasonal scaling rates, compared to the annual rate (Figure 1). Further seasonal differentiation into three seasonal periods indicates a slight negative scaling rate for the high-rainfall period (Dec-Mar), a result comparable to the annual scaling rate for Darwin where rainfall is summer dominant.

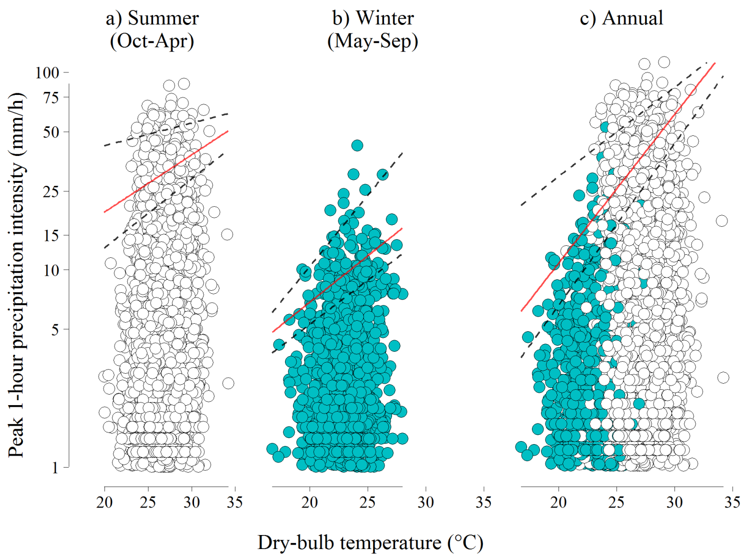

Figure 1. Estimation of scaling slopes for 90th, 95th (red line) and 99th percentiles through a quantile regression method using average dry-bulb temperature 12-hours prior to event start. Results are presented for (a) summer, (b) winter and (c) all months for Cairns Airport.

The results demonstrate that the seasonal analysis of temperature-precipitation sensitivities can result in altered scaling rates compared to annual-based analysis. Results indicate that during the peak of summer, the availability of moisture along the north-east coast, and not the increased moisture holding capacity of the atmosphere, is one of the main factors affecting precipitation-temperature scaling.

To account for moisture limitations, the use of dew point temperature in scaling calculations has been advocated as it is considered a direct measure of moisture availability. Additional work will include the use of both dry-bulb and dew point temperature as primary independent scaling variables.

Keywords: *Extreme precipitation, temperature, scaling, Clausius-Clapeyron*

Mapping of flooding risk hotspots along major highways using the AWRA-L water balance model

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Abstract: The Bureau of Meteorology is currently developing and evaluating a short-term to seasonal landscape forecasting system for hydrological variables – including soil moisture at different depths, runoff and evapotranspiration – using the AWRA landscape water balance model (AWRA-L). Previous analyses of the skill of the hydrological forecasts have shown good performance for different variables, regions and lead times and promising potential for a wide range of applications. To quantify the value of the hydrological forecasts for specific sectors, the performance and added benefit of the AWRA landscape forecasting system is assessed in case studies working closely with potential customers.

This study outlines the performance of the AWRA-L runoff forecasts at catchment scale, with a focus on the transport sector. In close collaboration with the Queensland Department of Transport and Main Roads (TMR), we investigated the skill of the AWRA-L nine-day runoff forecasts for predicting the risk of flooding of major highways, focusing on gauged catchments along the Bruce Highway. The Bruce Highway is a major highway in Queensland, with a length of approx. 1700 km, that connects the state capital, Brisbane, with Cairns in Far North Queensland, passing major coastal centres, including Townsville, Mackay, Rockhampton and Maryborough. It is one of the most critical transport infrastructures in Queensland and the biggest traffic carrier in the state. Flooding in one of the many rivers and streams that intersect the highway can cause the road to be closed at single or multiple locations, with negative economic impacts and potential risks to life and safety. Skilful forecasts of the risk of flooding several days ahead would provide an opportunity to prepare for the event and mitigate any potential negative effects.

We assessed the usefulness of AWRA-L forecasts in three steps: First, we defined critical runoff thresholds in collaboration with TMR that are linked to the risk of flooding. Subsequently, we identified events that exceeded the previously defined critical thresholds, in a) the observed streamflow using gauging station data (Zhang et al., 2013), b) the historical AWRA-L runoff data forced with historical climate observations (Jones, Wang and Fawcett, 2009), and c) the nine-day hindcasts of runoff based on AWRA-L forced with numerical weather prediction data (ACCESS-G APS2; http://www.bom.gov.au/australia/charts/bulletins/APOB105.pdf). In the last step, we assessed the agreement in the identification of critical events in the observations, historical simulation and hindcasts by calculating the Hit Rate (HR) and False Alarm Rate (FAR). This presentation provides an overview of the evaluation results and outlines potential applications for other regions in Australia.

Keywords: *Short-term forecasts, flooding risk, transport infrastructure, rails, roads*

A national hydrological projections service for Australia

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Abstract: Australia's water policy and infrastructure investment decisions require high-resolution information relevant to water resources taking into account both past and future variability. Existing information available to planners and resource managers exists for limited geographical regions such as single catchments, urban regions or states from multiple regional downscaling efforts and using different methods to interpret this data for hydrological impacts. These regional downscaling and hydrological impact data collections are either not application-ready or tailored for specific purposes only, which poses an additional barrier to their use across the water and other sectors.

There would be benefits in adopting agreed and consistent approaches nationally, including ensuring that policy and investment decisions are based upon an accessible, authoritative set of national climate projections for water, and that climate change risks are properly factored into infrastructure, investment and policy related decisions.

The Bureau of Meteorology is undertaking to produce an ensemble of consistent, national projections of the impacts of climate change on water and water related variables. The project aims to bring together several state-of-the-art downscaling techniques together with the CMIP5 ensemble to sample uncertainty along the impact modelling chain. Uncertainties due to downscaling of global circulation model (GCM) outputs are considerable and as part of this project, the currently available downscaled climate projections for Australia, both statistical and dynamical, will be evaluated and bias-corrected for use as an ensemble of downscaled climate data to force hydrological models. Hydrological indicators will be processed from the hydrological model outputs and presented together with key change and confidence messaging to provide application ready climate change impact data for the water sector.

The final service aims to support customers with both nationally modelled climate change impacts on water as well as hydrological model ready ensembles of downscaled climate inputs. In this presentation, we present an evaluation of an ensemble of bias-correction and downscaling techniques for simulating the hydrological impacts of climate change in Australia to consider methodological uncertainty, and present some of the results so far.

Keywords: *Climate change, hydrological impacts, climate services*

Global patterns of flood change: analysis of observed changes in the magnitude, frequency and drivers of extreme floods

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Abstract: Global warming continues to exacerbate extreme rainfall events, but whether and how these increases translate to changes in extreme flood events remain controversial. Whereas quantifying the changing magnitude and frequency of floods is crucial to optimizing our response to them. Based on streamflow observations collected from 7271 global catchments (mainly located at North America, South America, Europe, southern Africa and Australia), we identified extreme floods over the past decades (1979-2017) using a peak-over-threshold (POT) method for each catchment. Then, we applied a flood classification for identifying flood patterns by means of a fuzzy decision tree, and it showed that extreme flood events were mainly contributed by three patterns: Intense rainfall floods (IRF), snowmelt floods (SMF) and rain-on-snow floods (RoSF). During the past decades, extreme floods did not exhibit a substantial trend on average, with approximately 47% and 51% catchments experiencing an increase in flood magnitude and frequency, respectively. These regions are mainly located at northern and northeast America, central Europe, southern Africa and northern Australia. However, for catchments with all the three flood types, we find a widespread shift from snowmelt floods (SMF) to heavy rainfall floods (IRF) and rain-on-snow floods (RoSF). We also analyzed the correlation between extreme rainfall changes and extreme flood changes. Although changes in IRF are better related to extreme rainfall changes, more than 40% of catchments show negative correlations. Additionally, this correlation decreased significantly as the magnitude of flood increased. Meaningful generalizations about extreme flood changes across the globe and its relationship between extreme rainfall changes remain a subject of further research.

Keywords: *Flood magnitude, flood frequency, snowmelt, rainstorm*

Safety Protection Measures from Flare Stack through QRA (Quantitative Risk Assessment)

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Abstract: Chemical plants and industrial plants use large amounts of hazardous chemicals. They have a very large risk of fire, explosion and leakage due to fire, malfunction of the cooling system, runaway reaction, power failure, etc. during operation. Hazardous materials released through pressure control devices or safety valves installed in the process equipment are incinerated from the Flare Stack and released to safe areas in the atmosphere.

Therefore, the function of the Flare System is very important as a safety device to minimize the damage in the event of an accident, such as a leak, fire, or explosion. Flare Stack shall be installed in a safe location from the process equipment and after an accurate design review, such as capacity, height and gas composition of the Flare Stack, Tip Size, Knock Drum capacity, and radiant heat.

Korea's Industrial Safety and Health Act stipulates securing a 20-meter radius safe distance from the outside of the Flare Stack. The Korea High Pressure Gas Act and API-521 proposes Below 4,000 $kcal/hr \cdot m^2$ Radiation Intensity on the ground just below the center of the Flare Stack flame. Due to these criteria, the results of a quantitative risk assessment of the effects or protective measures on radiation heat, burn, explosion pressure, and toxic gas leakage on the facilities adjacent to the operator are not taken into account, human and material damage will occur in the event of the worst accident, and there is a high risk that the emergency response will be delayed and extended into a large accident.

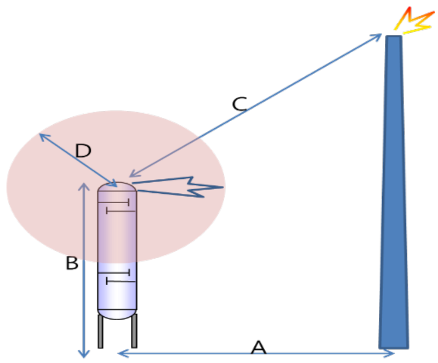

Figure 1. This picture shows the risk of a fire or explosion when flammable liquids and flammable gases are leaked, with flare stack and process equipment becoming sources of ignition

Keywords: *Flare system, tip size, knock drum, radiation intensity*

Identification of risk factors of lung cancer mortality in the American Poultry Workers using the Random Forest Algorithm

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Abstract: Workers of the poultry industry have one of the highest exposures to chemicals and oncogenic viruses: retroviruses and herpesvirus. These viruses commonly infect and cause cancer in chickens and turkeys. Poultry workers tasks such as raising, slaughtering, processing, and sale of raw poultry products expose them to these risk factors. Serological tests in this group clearly indicate widespread of these viral infections

The poultry workers have never been assessed before for long-term hazards associated with these exposures. In regards to chemicals, they are exposed the following chemicals: Polyvinyl chloride when they use plastic films to wrap meat; 2) Polyaromatic hydrocarbons when they inhale smoke emitted during smoking of birds ; 3) Heterocyclic amines, when they inhale aerosols emitted during frying of birds; and 4) nitrosamines when they add them to the spices. Additionally, these workers are among the lowest paid in the food industry. Therefore, their personal habits and surrounding environment (non-occupational factors) associated with low socioeconomic standards may contribute in their elevated risk for lung cancer. We conducted a large-scale case-cohort mortality study. The *source* population (N= 1160) for this case-cohort study, the total number of workers employed in poultry slaughtering/processing plants was 703 and the number of controls was 457. The random forest algorithm was used to fit classification trees. The data were randomly split into training (n=696) and validation data (n= 464). The training dataset was used to tune the number of trees required for the analysis. For the training dataset, the analysis results revealed the following: the required number of the trees was 300; the model accuracy was 85.4%; and the Area Under the Curve (AUC) was 83.7%. For the validation dataset, the model accuracy was 83.9 %; and the Area Under the Curve (AUC) was 82.4%. The most important variables associated with lung cancer were smoking, exposure to irradiation, eating processed food, killing chickens.

This study provides critical evidence for the first time, necessary to demonstrate the extent to which workers in poultry plants who are exposed to cancer-related risk factors. Measures should be implemented to protect them from these harmful workplace exposures.

Keywords: *Lung cancer, machine learning, occupational epidemiology*

Structural Equation Modelling approach to explore the relation of lead exposure and cardiovascular conductivity in the US general population

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Abstract: Lead is a common environmental toxin. Environmental lead exposure in the American population frequently happens when lead dust or fumes are inhaled, or ingested via contaminated hands, food, water, and cigarettes. When lead is inhaled or swallowed, it is released into the blood and gets distributed throughout the body. Because of the rapid industrialization and persistence of lead in the environment, lead exposure will remain a significant public health problem in the USA and other countries. Changes in electrocardiography (ECG) components and intervals reflect disturbance in cardiac electrical conductivity. Disturbance in cardiac conductivity has been associated with cardiovascular morbidity and mortality. Few studies have explored the effects of lead exposure on some of electrocardiogram (EKG) parameters. No study has ever evaluated the effect of lead on many of these components and intervals simultaneously. Therefore, in this study, we assessed the association between lead exposure and cardiac conductivity in a representative sample of the American general population, which participated in the National Health and *Nutrition* Examination Survey (*NHANES III*). The NHANES III is a population-based survey designed to collect information on the health and nutrition of the U.S. household population, and to obtain a representative sample of the non-institutionalized civilian US population. A total of 6,561 subjects aged 40 and above from NHANES III were included in our analysis. We excluded participants who had chronic heart diseases: ischemic heart diseases and heart failure. The data of NHANES III were collected by trained personnel according to standardized procedures. Socio-demographic information such as age, gender, race, and ethnicity was collected during the household interview. Laboratory measurements were performed in a mobile examination center. Blood lead concentration was measured by graphite furnace atomic absorption spectrophotometry and expressed in mcg/dl. Standard 12-lead ECGs, conducted during the medical examination, was used to detect ECG abnormalities and obtain durations and amplitudes of the ECG components. The ECGs were obtained for adults who were 40 years or older using the Marquette MAC 12 Medical Systems, Inc. (Milwaukee, Wisconsin). The 12-lead ECG recorded eight independent components simultaneously. Blood urea nitrogen levels were measured by the enzymatic conductivity rate method and serum creatinine levels were measured using the Jaffe kinetic alkaline picrate method. Glomerular filtration rate (GFR) was estimated by the modification of diet in renal disease (MDRD) study equation. The presence of microalbuminuria was defined as albumin-creatinine ratio >2.5 mg/mmol in men and >3.5 mg/mmol in women. We used a structural equation model (SEM) to explore the relationship between lead, kidney function, electrolytes, and cardiac conductivity. The latent and observed variables are shown in the graph. We used the following indices to evaluate the goodness of fit of the model: the goodness of fit index (GFI) was > 0.90, the normed fit index (NFI) was >0.90, and the root mean square error of (RMSEA) was < 0.04. Lead may have an effect on cardiovascular conductivity directly or indirectly. The results of the SEM analysis support the presence of potential biological pathways among lead, kidney, and electrolytes and cardiac conductivity. Nevertheless, these results should be interpreted in context of the cross-sectional design limitations. In summary, people who are exposed to environmental lead could be at high risk for impaired cardiac conductivity and adverse cardiac outcomes. Therefore, these people need to be checked periodically to detect cardiac conduction abnormalities early. Future studies are warranted to confirm the postulated mechanisms in this study.

Keywords: *Structural Equation Model, cross-sectional studies, NHANES*

Life prediction and verification of degradation mechanism of gasket for corrosive materials in PCB manufacturing process

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Abstract: This study has been progressed so that the accelerated life of each gasket material in a corrosive chemical handling process are estimated, the mechanism of degradation is identified, safety improvement measures and leakage accidents prevention are suggested. The contents of this study are as follows. First, the regulations and technical standards have been identified, and types and characteristics of gasket materials, the theory of degradation and the risk of degradation have been studied. Next, the two samples such as PTFE, EPDM were prepared to meet with accelerated degradation samples and normal samples. The accelerated degradation samples were immersed in a 35% aqueous solution of hydrochloric acid for 72 hours and then subjected to thermal stress at 100℃ for 72 hours in a dryer. After the thermogravimetric analysis, the activation energy was experimentally calculated using the Arrhenius equation. The accelerated life was predicted and the mechanical properties were compared and analyzed to verify its validity. Next, it has been analyzed whether the calculated accelerated life meets LOPA failure frequency. Finally, FE-SEM, EDX and FT-IR analyzes were conducted to identify the degradation mechanism, and a safety improvement method for degradation of the gasket was suggested.

TEFLON showed higher activation energy than EPDM in both normal and accelerated degradation samples. As a result of prediction of accelerated life under the set accelerated degradation condition, all of two samples were found to fail to meet the LOPA failure frequency (Gasket /Packing Blowout 10^{-2}/yr) under the operating condition. In the future, this study suggested that the frequency of LOPA failure should be revised and checked through further studies on accelerated life and failure rate. As a result of FE-SEM, EDX and FT-IR analysis, in the case of EPDM, the side chain of the diene was attacked by chlorine to chlorinate the methyl group. These cases verified the degradation mechanism. In addition, the TEFLON samples showed that stable binding of carbon and fluorine, and activation energy and accelerated life were not significantly changed by accelerated degradation. In EPDM, the elongation rates of accelerated deteriorated samples were decreased. The relationship between activation energy and mechanical properties calculated by thermogravimetric analysis was inconsistent. On the basis of these results, limitations of IEEE Std 1205-2000 Arrhenius degradation model, activation energy and accelerated life prediction are applied to a single degradation pattern with respect to temperature and time, have been verified. In other words, in case of EPDM accelerated degradation samples, activation energy and accelerated life calculated by thermogravimetric analysis are not effective due to the chemical behavior of hydrochlorination reaction. However, in case of TEFLON accelerated degradation samples, its chemical behavior was not found, and it was judged that the calculated activation energy and accelerated life were valid. And for plastic materials such as TEFLON have high chemical stability, it was suggested that the minimum life period setting criteria for chemical storage tanks should be set up by using the accelerated life prediction method. Therefore, polymer composite rubber gaskets have different safety and life of chemical materials depending on their blending characteristics. So, it was recommended that the standards for the manufacture, selection and installation of gaskets should be supplemented in detail, and the individual packaging and the usability of the product for prevention of oxidation during distribution should be indicated on the packaging container. Finally, since the degradation of the gasket is accompanied by a change in physical properties, manufacturers should provide the safety installation information by testing the product-specific standard to set up a flange tightened bolt at a proper torque.

Keywords: *Activation energy, Life Prediction, degradation mechanism, gasket, TEFLON, EPDM*

A Bayesian paradigm of the disparities in the relation of alcohol and acetaminophen in early stage kidney toxicity

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Abstract: We previously explored and reported the relation of light to moderate alcohol (LMA) consumption concomitantly with therapeutic doses of acetaminophen (APAP) in the risk of renal dysfunction among adults in the United states. To assess potential disparities in the above relation among gender, racial, age and socioeconomic subgroups the results were analyzed using Bayesian paradigm. Based on Baye's Theorem, the information obtained from the 2003–2004 US National Health Examination Survey (NHANES) were examined, and the data updated with data from the Synthetic Derivative (SD) from the Northeast (NE) Texas region. The SD is a de-identified, non-relinkable copy of a NE Texas hospital electronic medical record. The results of this study found that renal disease, as determined by self-reports and laboratory measurements of serum creatinine (SCr) and Glomerular Filtration Rate [GFR], albumin/creatinine ratios [A/CTNE ratio] values of 1.0 mg/dl and 90.0 ml/minute/1.73m2, respectively, may occur, marked by statistically significant odds ratios among those who concomitantly ingested therapeutic doses of APAP and ingested LMA when compared to those who did not ingest the above agents. These were more profound among females, minority racial groups (Blacks in particular), those below legal drinking age of 21, high school grad and college freshmen, and the poor with household income below 25K. While these results may be telling, it is important to further explore the exact role of LMA and other potential predisposing factors in the relation of acetaminophen toxicity to the kidney. This this study further elucidated both methodological and non-methodological factors to be considered in the design and implementation of larger scale epidemiologic studies on the interaction of alcohol and APAP in the development of early stage renal dysfunction.

Keywords: *Acetaminophen, Bayesian, NHANES*

Sampling schemes for selecting control in a nested case-control cancer mortality study: An empirical comparison

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Abstract: This study was designed to compare effect estimates following different schemes for selecting controls in a nested case-control study investigating lung cancer mortality among workers in poultry slaughtering/processing plants. These workers have a high exposure to oncogenic viruses compared to the general population.

Data from the ongoing Cancer Risk in Workers Exposed to Oncogenic Viruses (CRIWETOV) project for members in a local Union Pension Fund belonging to the United Food &Commercial Workers (UFCW) international union was utilized. The workers were followed–up for mortality from January 1, 1972 to December 31, 2003. This cohort was comprised of workers in poultry slaughtering/processing plants and non-poultry workers. The sampling schemes for selecting controls in this nested case-control study were the cumulative survival, cumulative incidence, case-cohort, and incidence density sampling schemes and were analyzed using logistic regression models.

The entire cohort and subgroups of poultry and non-poultry workers separately had higher risks of mortality from this malignant disease compared to the United States' general population, but slightly lower risks among poultry compared to non-poultry workers. Effect estimates were similar for nested case-control analyses that applied the cumulative survival, cumulative incidence and case-cohort sampling schemes in selecting controls. However, the incidence density sampling scheme led to markedly different results. Although results were similar for some schemes, the data still needs to meet different specific underlying assumptions for the application to be valid. For incidence density sampling, a possibly different analytical approach from logistic regression may be required.

Keywords: *Nested Case-Control, lung cancer mortality, incidence density sampling*

EXTENDED ABSTRACT ONLY

Key role of clients and contractors in chemical factory construction to solve health and safety problems

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Abstract: In Korea, recent construction's fatality rate representing the number of deaths per ten thousand workers tends to increase while all industries' fatality rates were on the decline. For example, the official fatality rate in Korea's construction industry in 2017 was 1.90 that was 1.83 times higher than that of the manufacturing industry. Since the accident occurred in the construction of the chemical factory used to lead public concern, the Korean construction clients meaning the owner of the chemical factory has a strong concern on the construction accident. In addition, they require a strong health and safety management system higher than other construction sites to contractor and subcontractors.

In this paper, the key role of clients, contractors, and subcontractors was investigated by the site inspection and audit. During the 1 year, regular site inspection and audit were performed weekly. In addition, interview was implemented to safety managers belonging to clients and contractors.

The key roles of construction clients is to inspect construction site daily by safety managers belonging to clients and to provide a sufficient sources such as period and cost to solve health and safety problems. Most clients did not inspect and see their construction site since they did not know the construction process. However, the basic knowledge and viewpoint about the construction health and safety management system is not different to other industries. Clients' active inspection can lead a high level health and safety management system of contractors. In addition, clients do not hesitate to provide a sufficient construction period and cost to contractors since the shortage of construction period and cost is one of the main fatal accident in Korea.

The contractors is the main body in establishing and implementing the health and safety plan. However, most contractors thought the only safety managers should have a duty of health and safety problems. Other managers such as construction and engineering managers tends to be uninterested in health and safety problems in sites. Thus, all managers in contractors should give attention and have R&R (role and responsibility) to the health and safety management. For subcontractors, they should establish health and safety management system. Unlike contractors, most subcontractors did not have a health and safety management system in company level. Thus, subcontractors have a trouble in following the high level health and safety management required by clients.

The proposed key roles to clients, contractors, subcontractors can help reducing the major accidents in chemical factory construction in Korea.

Table 1. The proposed key role of construction participants in Korea chemical factory construction

Classification	Key role
Client	· Inspect construction site regularly by safety managers belonging to clients · Providing a sufficient sources in solving health and safety problem
Contractor	·Give a health and safety role to all managers including construction managers, safety managers, and health managers.
Subcontractor	·Establish health and safety management system

Keywords: *Integrated modelling, integrated assessment frameworks, conceptual model*

A flexible family of hypertabastic models

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Abstract: Survival analysis is a major tool in cancer research, with a wide application in modeling a variety of cancer survival time data. The family of hypertabastic models includes the hypertabastic proportional hazards model and the hypertabastic accelerated failure model. The hypertabastic survival model has been applied to analysis of various types of cancer data including breast cancer, multiple myeloma, and glioma and to the analysis of non-cancer data. In the area of medical genomics, Tabatabai et al analyzed breast cancer data using clinical and multiple gene expression variables using the hypertabastic proportional hazards model and compared the results with Cox regression. Compared with Cox regression, the increase in accuracy was complemented by the capacity to analyze the time course of disease progression using the explicitly described hazard and survival functions. Recently the hypertabastic accelerated failure models have also been used to analyze mylar-polyurethane insulation data. This gives a new dimension in the application of hypertabastic survival models in biomedical settings. In his paper, we discuss the family of flexible hypertabastic models with applications in cancer.

Keywords: *Time-to-event data, proportional hazards model, hyperblastic models, goodness of fit test, multiple gene expression*

Development of a dynamic simulation model to estimate the impact of various policy options on alcohol consumption in the Australian Capital Territory

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Abstract: While many Australians perceive methamphetamines (including ice) to be the drug of most concern to the community, alcohol remains Australia's most extensively used drug. In 2016, around 80% of persons aged 14 years and older in the Australian Capital Territory (ACT) were classified as current drinkers, while 40% consumed at least weekly

Alcohol consumption is associated with liver, breast, mouth and pharyngeal, bowel, laryngeal and oesophageal cancers, and in the ACT accounts for 4.2% of the total disease burden, making it the fourth-highest risk factor leading to ill-health. In addition, alcohol use accounts for 24% of the disease burden associated with chronic liver disease, as well as 23% for liver cancer, 21% for laryngeal cancer, 19% for homicides and violence, 17% for suicide and self-inflicted injuries, 16% for drownings and 11% for all falls. Alcohol use also impacts the services provided by ACT Health, with the 2018 ACT Chief Health Officer's report indicating that emergency department presentations for alcohol-attributable injuries had increased by an average of 4.2% per year between 2012/13 and 2015/16.

In Australia, responsibility for developing policy, programs and services to reduce alcohol-related harms is shared between states, territories and the federal government. It is important that responses to alcohol consumption are developed in consultation with appropriate stake-holders and utilise rigorous evidence and research. This collaborative project involved epidemiologists, researchers, policy officers and computer scientists working together to develop an agent-based dynamic simulation model designed to support the development of population health-based policy initiatives. Once developed, this model will help to inform priority policy questions on how to minimise alcohol-related harms at the population level in the ACT.

The alcohol-use model explores strategies to limit acute and chronic harms from risky alcohol consumption. It describes a population of Person agents who can drink alcohol at drinking events. Once per day, all people have the chance to attending a drinking event, either with their peers or on their own. People must also make alcohol purchasing decisions, which provides a constraint on the amount of alcohol available for consumption. The amount people consume in a given night is impacted by their goal, the effects of intoxication, and the drinking behaviour of any friends at the same event. Model outputs include overall alcohol consumption in solo and social contexts, and levels of chronic and acute alcohol-related harms.

The model has a primary intervention: a minimum price per standard drink.

Keywords: *Dynamic simulation, alcohol, policy*

"Stopping before you start": Reducing and preventing initiation of tobacco use in the ACT

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Abstract: Tobacco is the leading cause of preventable death in Australia and contributes to 5.4% of disease burden in the Australian Capital Territory. Initiation of tobacco use is most likely to occur during adolescence and young adulthood (at less than 20 years). Prevention of tobacco initiation involves a combination of regulatory, educational and health promotion interventions including restrictions on the sale of tobacco products. This paper reports on the development and use of an agent-based model to explore the impact of modifying three hypothetical regulatory and health promotion interventions: 1) increasing the minimum purchasing age for tobacco products, 2) reducing retail sales of tobacco products to persons under the minimum purchasing age and 3) reducing secondary sharing of tobacco products to persons under the minimum purchasing age using health promotion messaging. The model was built using a participatory approach that engaged policy officers, health promotion officers, epidemiologists, biostatisticians and computer scientists. The structure of the model included interacting state chart representations of smoking and level of concern about tobacco use (engagement status) and a pro-smoking score, which defined the hazard rate of initiation, cessation, and relapse. The pro-smoking score was a function of several risk factors including engagement, social effect of having more or fewer smoking peers, addiction and withdrawal levels and access to tobacco products. Parameterisation of the model drew on a range of data sources with local data being prioritised where it was available. A series of scenarios comparing the impact of the interventions on smoking prevalence rates and age of initiation are reported. Of the three interventions simulated, increasing the minimum purchasing age from 18 to 21 years had the greatest impact on smoking prevalence across the population, reducing the prevalence of smoking from 8.5% (95% CI 7.8, 9.2) to 6.9% (95% CI 6.4, 7.4) five years post-intervention and 4.1% (95% CI 3.8, 4.3) 20 years post intervention (Figure 1). The interventions aimed to reduce the sale of tobacco products to minors and reduce secondary sharing produced small reductions on their own. However, when implemented in combination with increasing the minimum purchasing age, they significantly increased the impact of this intervention from ten years post-implementation, ultimately resulting in a prevalence rate of 2.8% (95% CI 2.6, 3.0) 20 years post-implementation. Given the challenges associated with ceasing tobacco use, these *in silico* experiments demonstrate the importance of regulatory public health interventions to delay, and therefore potentially prevent initiation.

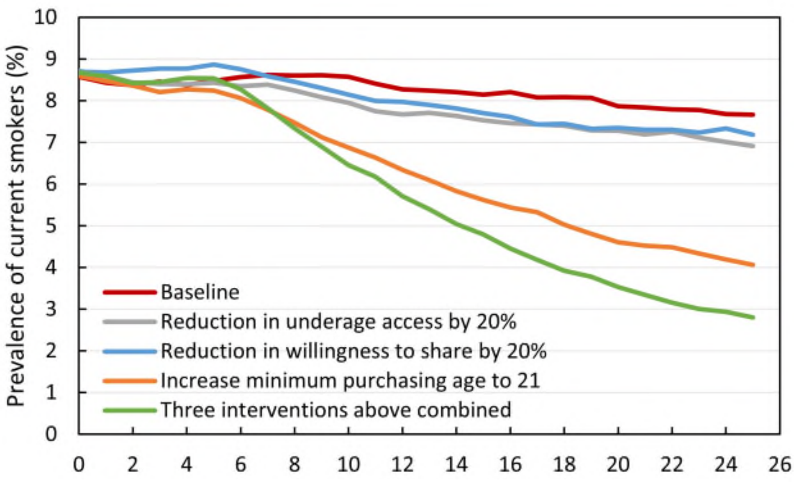

Figure 1. Simulated change in prevalence of current smokers for intervention strategies. Interventions start at year 5.

Keywords: *Tobacco use, health modelling, agent-based*

Children's Environmental Health in the Solomon Islands – a modelling approach to problem solving in a data poor environment

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Abstract: The Solomon Islands is one of only two 'least developed countries' in the Western Pacific region and one of the most environmentally vulnerable countries in the world, with local and distal pollution issues and low levels of access to clean water, sanitation and clean cooking fuel. Climate change is an existential threat to many communities, threatened by environmental changes such as sea level rise and increasing tropical storm activity. The current and past health impacts of these issues are uncertain, as are the future health risks.

In common with other Pacific Island countries, the Solomon Islands has a paucity of primary health data due to poverty, lack of resources and the remoteness of much of the population. However, in key measures of children's health, what data there are indicate no improvements, and possible declines over a ten year period. The country features in global databases such as the Institute of Health Metrics Evaluation's Global Burden of Disease database but much of the environmental health information provided by these databases is estimated from modelling rather than hard data.

Initial research shows significant differences between the modelled health data for the Solomon Islands, expert opinion, public health policies and donor investment in environmental health.

Initial investigation also indicates that, despite investment in many areas such as mosquito control, immunization, supply of clean water and sanitation initiatives, there has been no significant improvement over a ten year period in key health indicators such as childhood mortality associated with environmental determinants. Predicted climate change-related environmental changes will disrupt water supplies, degrade air quality, increase disaster frequency and drive vector proliferation as habitation areas expand. All these changes will expose children to increased environmental hazards.

The research seeks to understand the extent to which environmentally related causes influence health outcomes for the children of the Solomon Islands and to explore and propose policy / strategy options for environmental health protection and improvement. It aims to close the knowledge gaps by modelling the linkages between environmental causes and children's health outcomes using Systems Dynamics techniques. A community based system dynamics approach is planned to be used with stakeholders in the Solomon Islands to gain understanding of the relationships operating in the system. Causal loop diagrams will be built during this activity, enabling the relationships to be visually communicated and validated. Dynamic modelling and simulation will then be used to improve understanding of the system and to test alternative policies and scenarios.

This poster presentation will report on the research undertaken so far, the modelling approach adopted and the challenges of system dynamics modelling in the Solomon Islands. It will show how we plan to deal with uncertainty, lack of data and poor quality data in a country where data limitations are a major barrier to research in the area.

Keywords: *Integrated modelling, system dynamics, environmental health, health information, Pacific Islands*

Particle based Droplet Simulation in Liquid-Liquid Two-phase Flow

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Abstract: The subarachnoid hemorrhage is a disease that damages brain function by rupture of cerebral aneurysm and, at the worst case, it leads to death. The subarachnoid hemorrhage is one of the dangerous diseases in Japan. And, clipping and coil embolization are selected as the preventive surgery; however, these surgeries do not have enough effect for distorted shape or enormous size of the cerebral aneurysm. On the other hand, liquid embolization that injects an embolic material having chemical curing property into the aneurysm is also used overseas. Liquid embolization can treat a distorted shape or enormous size of aneurysm that clipping and coil embolization cannot treat. However, liquid embolization has not been approved in Japan because there is a risk that the injected embolic material might flow out of the aneurysm and embolize peripheral blood vessels.

Then, we have developed an embolic material injection simulation using a particle method as a preliminary stage to validate the safety of the liquid embolization simulation, and have performed the quantitative evaluation by comparing the simulation result with the physical experiment in order to control the embolic material injection. In the study, we have performed the injection simulation of embolic material, which is injected from a circular tube imitating a catheter into a water tank imitating a cerebral aneurysm. In the previous research, however, the formed droplet did not contact with the tip of the circular tube.

Therefore, we consider that the previous simulation results are due to the interfacial tension model, and in this paper, we solve the problem by reconsidering the interfacial tension model. The interfacial model used in the previous research considered only the intermolecular potential force of in a single fluid. However, we have to consider the intermolecular potential force between different liquids because water in the water tank and the embolic material injected through a catheter are different. Therefore, we newly adopt an interface tension model that can consider the influence from the other liquid on the boundary of two different liquids. In this paper, we propose an interfacial tension model that considers liquid-liquid two-phase flow because the reference model of the potential force for two different fluids treats gas-liquid two-phase flow. As the result of the simulation, we have confirmed that the droplets formed by the simulation contacts with the tip of the catheter.

Figure 1 shows the result of the simulation. In the figure, the black line on the top of the droplet shows the tip of the catheter. In Figure 1 (a), the droplet does not contact with the tip of the catheter, while it contacts with the tip in Figure 1 (b).

Time = 1.03[s]

(a) Previous model (interfacial tension model for single liquid) — (b) Proposed model (interfacial tension model for two different liquid)

Figure 1. Simulation results for the previous and the proposed models.

Keywords: *Physical simulation, particle method, liquid-liquid two-phase flow, interfacial tension*

A new Maxwell paired comparison model: application to a study of the effect of nicotine levels on cigarette brand choices

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Abstract: In this article, we propose a new choice model to assess the influence of nicotine level over the choice behaviors of smokers in selecting different brands of cigarette. The objectives of the study are met by considering three most commonly used cigarette brands in Pakistan, which are Benson & Hedges (BH), Marlboro (Ma) and Gold Leaf (GL). The data are gathered through a balance paired comparison (PC) experiment where 150 smokers, aged 25- 35 years, are asked about their preferences to the aforementioned brands.

An initial exploratory analysis of the data reveals that, in general, smokers prefer cigarette brands with a higher level of nicotine. We observed that almost 65% of the participants reported they prefer Gold Leaf brand (nicotine level 16.92 ± 0.82 $mg/stick$) over Marlboro (nicotine level 12.95 ± 0.82 $mg/stick$). Moreover, when choosing between Gold Leaf and Benson & Hedges (nicotine level 15.93 ± 0.69 $mg/stick$), around 59% recorded their preference for Gold Leaf over Benson & Hedges. Lastly, the comparative choices of the participants of our study favor Benson & Hedges over Marlboro, where almost 55% of the respondents reported that they prefer Benson & Hedges. Thus the overall preference ordering of choice behaviors based on this study can be written as $GL \rightarrow BH \rightarrow Ma$. The comparative information is then modeled by introducing a new choice model based on the Maxwell distribution. Estimation of the worth parameters and associated preference probabilities is performed by means of *Gibbs Sampling*, where two non-informative priors, the Uniform and Jefferys priors are used.

We observed that both priors are capable of retaining true preference order, however the Jefferys prior performs better as compared to the Uniform prior by closely estimating the observed extent of preferences. The estimated values of the worth parameters reveals that cigarette brand preferences are associated with higher levels of nicotine and thus we verify the findings of our initial analysis via the Maxwell distribution based choice model. For example, regardless of the prior distribution, highest utility is attached with the Gold Leaf brand (highest nicotine level), followed by Benson & Hedges and then Marlboro. Using the Jefferys prior, we observed an estimated value of the worth parameter of 0.3765 highlighting preference of Gold Leaf brand, associated with a 0.6492 value for the preference probability. Further, in the case of the second most preferred brand, namely. Benson & Hedges, the estimated worth parameter has a value of 0.3247 which is associated with a preference probability equal to 0.5927. Similarly, the estimated worth parameter underlying the choice of Marlboro brand is 0.2981 which approximates with a preference probability of 0.5599 - therefore Marlboro remained the least preferred brand. We observed similar trends in the choice behaviors when the Uniform distribution was used as a prior.

In conclusion regardless of the prior distributions, we observed common trends in the choice behaviors. For example, with respect to the both priors, the highest value of the worth parameter is associated with the GL brand, which also has the highest reported nicotine level. The GL brand is then followed by BH brand, with which the second highest value of worth parameter and nicotine level is attributed. The minimal value of the worth parameter is associated with the Ma brand which has the lowest level of nicotine among the three studied brands. The posterior standard deviations revealed that the Jefferys prior provides more stable estimates of the worth parameters as compared to Uniform prior

This paper contributes a new PC model, named the Maxwell paired comparison model to the literature. The applicability of the newly proposed comparative model is demonstrated. We have also established that nicotine level plays an instrumental role in driving the preference ordering of cigarette brands. We conclude that smokers in general tend to choose a cigarette brand with higher levels of nicotine. Public health interventions could potentially address this via public health warnings and intervention/education programs.

Keywords: *Choice behaviors, comparative models, Maxwell distribution, worth parameters, priors*

Copula modelling of agitation-sedation rating of ICU patients: towards monitoring and alerting tools

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Abstract: Agitation-Sedation (A-S) cycling in critically ill intensive care unit (ICU) patients is damaging to health. Sedation quality is assessed by nurses and may suffer from subjectivity in their judgment and lead to sub-optimal sedation. Therefore, the use of quantitative modelling to enhance understanding of the A-S system is a key tool for optimising sedation management. Inadequate assessment of the agitation associated with clinical outcomes may lead to under or over-sedation and harm a patient's wellbeing.

Empirical distributions of the nurses' ratings of a patient's pain and/or agitation levels and the administered dose of sedative are often positively skewed and if the joint distribution is non-elliptical, then the high nurses' ratings of a patient's agitation levels may not correspond to the occurrences of patient's A-S profile with large infusion dose. Copulas measure nonlinear dependencies capturing the dependence between skewed distributions. Therefore, the aim is to use a copula-based dependence measure between the nurses' rating of patients' agitation level, and the automated sedation dose to identify patient-specific thresholds that separate the regions of mild, moderate, and severe agitation intensities. Delineating the occurrences with different agitation intensities allows us to establish the regions where nurses' rating has stronger or weaker correlation with the automated sedation dose.

This pilot study modelled agitation-sedation profiles o f t wo p atients c ollected a t C hristchurch Hospital, Christchurch School of Medicine and Health Sciences, NZ, from the pool of 37 patients. Classification of patients into poor and good trackers based on Wavelet Probability Bands (WPB). One of the patients is a poor tracker and the other patient is a good tracker. The best-fitting c opula s hows t hat t he d ependency structure between the nurses rating of a patients agitation level and the administered dose of sedative for both patients has an upper and lower tail. More specifically, a correlation between the nurses rating of a patients agitation severity and the administered dose of the sedative is the strongest when patients are expressing signs of a mild agitation, namely in the lower tail region (below the lower threshold for nurses' rating: 1.1 for poor tracker and 1.3 for good tracker) and weakest when patients are expressing signs of a severe agitation, namely in the upper tail region (above the upper threshold for nurses' rating: 2.6 for poor tracker and 6.1 for good tracker). The results show that for a good tracker, the nurses' rating of the patients' agitation levels has strong positive correlation with the administered dose of the sedative for low and mild agitation severity. For a poor tracker, the nurses' rating of the patients' agitation levels has strong positive correlation with the administered dose of the sedative only for low agitation severity. In addition, incorporating the tail dummy variables improved predictions of the nurses' rating by increasing the adjusted R^2 values by 28%. Moreover, the percentage of lower and upper tail observations that are common with the lower and upper WPBs is higher for the poor tracker than the good tracker. However, the percentage of observations that are common to both the main region (the region associated with moderate agitation intensity) and within WPB is higher for the good tracker compared to the poor tracker.

In this paper we have accounted for non-linear relationships between the two variables, finding thresholds and regions of mismatch between the nurse's scores and sedation dose, thereby suggesting a possible way forward for an improved alerting system for over/under-sedation. Establishing the presence of tail dependence and patient-specific thresholds for areas with different agitation intensities has significant implications for the effective administration of sedatives. Better management of A-S states will allow clinicians to improve the efficacy of care and reduce healthcare costs.

Keywords: *ICU, copula modelling, agitation-sedation assessment, nurses' rating, waverlet band*

Skin groups and Onan: computer simulation as an aid to understanding anthropological phenomena

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Abstract: When studying anthropological and social phenomena, it is important to evaluate them on their own terms. Agent-based computer simulation is a tool that can assist with understanding the function of such phenomena in the context of the social fabric of which they are part. Simulating key aspects of a society with and without a particular feature allows us to answer the question "what does this feature actually do?"

In this paper we demonstrate the utility of agent-based computer simulation in this regard by exploring two quite different social phenomena: Australian Aboriginal "skin groups" and the "levirate duty" of the ancient Hebrews. In both cases, the context of the phenomena (in each case, a sacred foundational story and a law) suggests a degree of importance.

Australian Aboriginal "skin groups" are intimately involved with ceremony and society in many ways. In particular, they restrict allowable marriage and they play a part in the transmission of oral culture. The agent-based NetLogo simulation reported here showed that the "skin group" system has genetic benefits, in that it reduces the death rate due to recessive lethal genes. It does this primarily by encouraging exogamy. It also increases the survival rate of stories which encode knowledge vital to a tribe's long-term survival.

Our skin group simulation used one particular well-documented skin group system, that of the Lardil people. This system has the structure of the dihedral group D_4. We compared this "skin group" system (with and without allowing women to marry older men) against two simple incest taboos. Our simulation included births, marriages, genetics, and the transmission of stories. Table 1 summarises the results of this simulation.

We also simulated the effect of the "levirate duty" of the ancient Hebrews, which is recorded in the Hebrew Scriptures (among other places, in the story of Onan), but which pre-dates that written account. Our simulation included births, property, and marriages, as well as ancient Hebrew inheritance laws and incest taboos. This simulation was less conclusive, showing little effect of the "levirate duty" on social inequality (as measured by the Gini coefficient). This provides weak support for theories indicating that it had some other purpose than social justice (such as providing children to childless widows, or providing a kind of spiritual continuity to childless men).

In both case studies, however, the phenomena could be successfully modelled using an agent-based simulation, and the results of the simulation shed useful light on the purposes of the phenomena being examined.

Table 1. Values and 95% confidence intervals for simulation outputs of our Australian Aboriginal "skin group" simulation.

	Simple incest taboos		**Skin groups**	
	No siblings	**No cousins**	**Basic**	**With marriage to elders**
Death rate due to recessive lethal genes (per 100,000)	**500.5** (490.8–510.1)	**482.0** (472.9–491.0)	**53.6** (49.2–57.8)	**146.3** (139.1–153.2)
Percentage of marriage with outsiders (exogamy)	**4.23%** (4.20–4.26)	**4.26%** (4.23–4.29)	**51.1%** (50.1–52.1)	**24.1%** (23.2–24.9)
Mean number of surviving stories (transmitted in the paternal line)	**0.70** (0.51–0.88)	**0.91** (0.70–1.11)	**7.19** (7.04–7.36)	**7.87** (7.82–7.94)

Keywords: *Agent-based modelling, NetLogo, Anthropology, Skin groups, Levirate marriage*

Modelling impacts of inorganic UV blockers used in sunscreens on marine environment

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Abstract: Titanium dioxide (TiO_2) and zinc oxide (ZnO) nanoparticles are commonly used as inorganic UV blockers in providing effective UV protection. However, recently, their use is under scrutiny because of the potential risks to consumers and the marine environment. For example, in contact with water, sunlight and oxygen, the two UV filters begin forming significant amounts of chemical compounds such as hydrogen peroxide, which destroys microalgae that are critical for coral reefs' health. Coral reefs are essential for the marine ecosystem and the coastal communities for food security, recreational activities, and natural barriers in reducing the impact of extreme events such as cyclones, storm surge and tsunamis. However, coral reef health has been exacerbated by the changing climate, rapid urbanisation, and population growth. Human activities cause the release of thousands of tons of sunscreen into the marine environment each year, resulting in further deterioration. Therefore, this research aims to build a Scenario Risk Assessment Model using System Dynamics to identify the potential health impact of nano-TiO_2 on humans and the marine ecosystem. Further, the chemical changes that nanoparticles undergo during their life cycle are also investigated and correlated with the environmental impact. In this context, the depletion of the protective coating of TiO_2-nanoparticles will be assessed in the sea and the swimming pool water. The expected outcome of this study has the potential to provide comprehensive and reliable information to government and community stakeholders about the risks of these two UV filters. Additionally, as this problem is of economic and social importance, the knowledge resulting from this research could help develop strategies to reduce the future costs of environmental restoration with associated economic benefits.

Keywords: *Risk assessment modelling, nanoparticles, inorganic UV filters, sunscreens, coral reefs*

A participatory geographic modeling platform: Solving complex geographic problems through collaboration

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Abstract: In order to cope with complex geographic problems, interdisciplinary research is widely needed. The cooperation among experts and stakeholders who focus on different fields is necessary for the solving of the complex geographic problem. The CSCW (Computer Supported Collaborative Work) technology has been increasingly integrated into GIS (Geographic Information System) for satisfying the participatory working demands. And such approaches are important to address geographic problems through collaboration. However, the existing methods for solving geo-problems collaboratively still encounter limitations, especially, in the perspective of the member organization and resources sharing. Furthermore, a universal working pattern of solving processes is also needed for a wide range of geographic problems.

Focused on the above demands and limitations, this paper developed a participatory modeling platform in the web environment which consists of three cores as project management, role-based user control, and resource sharing. In the project management aspect, a project can be divided into several subprojects so that participants can divide the process of solving a complex geographic problem into different steps. Meanwhile, users involved in a project can be identified as different roles, including visitors, participants, subproject managers, and project managers and a user will be assigned with different management and operation authorities according to his/her role. Resources sharing provides functionalities that resources which are helpful for solving the problems designed in a project or subproject can be uploaded and shared among different participants.

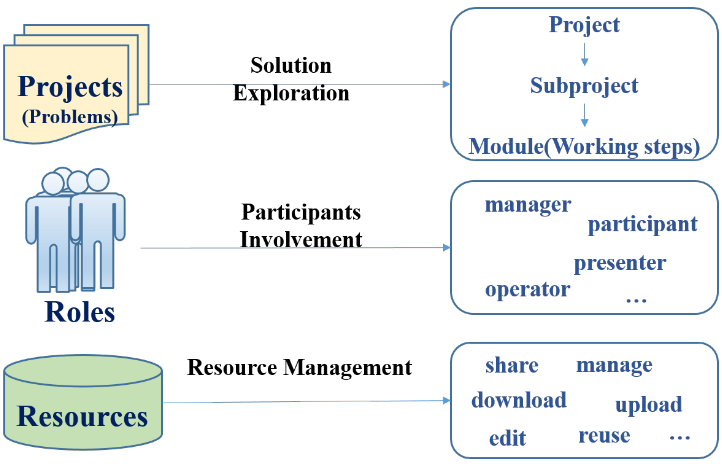

Figure 1. The proposed participatory modeling framework for solving geo-problems through collaboration

Various geographic problems existing in the Earth environmental system (which is an extremely complicated system), such as global warming, water pollution, air quality issues and so forth. The process of solving these problems can be described as the exploration attempts for suitable solutions. Based on the feature of a geographic problem and the shared understanding of the cooperation team, an exploration process can be formed with six basic modules, including preparation, analysis, modeling, simulation, validation, and comparison. In addition, several collaborative tools and communication tools are developed for these six modules and can be used for sharing ideas and discussing opinions. Thus, each participant in a project can contribute his/her own ideas and resources by creating a new module or undertaking the tasks defined in an existing module. Based on the functionalities provided by the prototype Participatory Geographic Modeling platform, two experimental cases were conducted to verify the feasibility and capability.

Keywords: *Participatory platform, Geographic problem solving, Collaborative modeling, Geographic process, inter-disciplinary collaboration*

Combining conceptual models and expert elicitation for estimating and monitoring species' response to management

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Abstract: Threatened species management often occurs against a background of complex ecological systems, limited knowledge and restricted resources. Ensuring effective management via adaptive management practices is therefore crucial for securing a species survival. Monitoring and evaluation plans, including the selection of realistic target values for suitable indicators, play a central role in this. In order to set these values, managers need to consider how different system components (include threats, competitors and dependencies, as well as the species itself) will respond to the proposed management intervention. This task can be particularly challenging when data driven modeling techniques are infeasible due to lack of data or modeling expertise. In these data poor situations, structured expert elicitation approaches can be used to combine knowledge from multiple experts, including project coordinators, site managers and external species experts such as academics and members of community non-government organisations. However, while many of the rigorous expert elicitation protocols now considered as best practice require multiple experts over multiple elicitation rounds, many species will have only a few experts. Furthermore, existing guidelines often require experts to make estimates for distant time periods or covering large geographic regions, such as a region or country, which can be a daunting task and fails to record the mechanics behind their decisions.

We present a five step framework (Figure 1), developed in conjunction with the New South Wales (NSW) Department of Planning, Industry and Environment, Saving our Species (SoS) programme, that helps to overcome these limitations by combining conceptual modeling with a simple structured expert elicitation exercise that can be used either in a facilitated setting or by experts working alone or in small groups. The framework was refined the through a series of five user workshops and 12 threatened species cases studies covering a range of taxa including both plants and animals. The step by step guidance on designing an influence diagram which links a species with the threats it faces and the proposed management interventions, allows experts to combine and formalise their knowledge of the system and provides transparency for decision making. Values for indicators are elicited in at a site level, for short timeframes, and for different management scenarios using a four step elicitation approach (requiring values fort the highest, lowest and most realistic values at each time point, as well a measure of confidence).

The framework is unique in that it provides accessible and easy to follow guidelines for the entire process, providing decision makers with a practical tool to combine expert opinions, the outputs from which (influence diagrams, response to management curves and management targets) can be directly including into adaptive management plans. This facilitates informed and transparent decisions making despite the system complexity. In doing so it helps to secure as many species as possible from the threat of extinction.

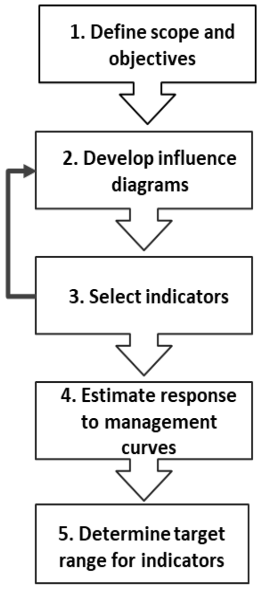

Figure 1. Framework for selecting targets to monitor species' response to management

Keywords: *Threatened species monitoring, conceptual models, expert elicitation*

Development of an integrated model to evaluate impacts of climate change on malaria risk at the community level – A systems approach

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Abstract: Malaria is a mosquito-borne parasitic disease that is responsible for over half a million deaths each year, mostly in sub-Saharan Africa. The disease is sensitive to climate change and climate variability, particularly in the highland of East Africa where increases malaria incidences and epidemics have been linked to a corresponding increase in average temperatures and changes in rainfall in the region. The malaria transmission cycle is complex and is additionally influenced changes in land use, human behaviour, and other environmental, socio-economic and socio-cultural factors at local levels. The non-linear interactions between these factors makes it challenging to provide a reliable assessment of climate change and malaria risk and to design suitable and targeted interventions further.

Malaria is the most studied mosquito-borne disease in the context of climate change, and both biological and statistical models of risk have been developed at a global and regional level, however, these models have not adequately addressed the associated uncertainty and the non-linear interactions between influencing factors. Another component is the probabilistic nature of factors influencing malaria transmission, which are not well represented by the deterministic nature of these models. Finally, adaptations or modifications of human behaviour in response to projected climate change and malaria risk can change risk profiles and therefore need to be considered beyond the limitations of static models.

Bayesian Networks (BNs) models have been proposed as a solution to address some of these limitations of the previous modelling. BNs are modelled on probability distributions and can handle uncertainty well, making them suitable for modelling complex systems and sub-systems. Additionally, BNs can accommodate both quantitative and qualitative data input from a variety of sources and can be used for the analysis of scenarios of risk and possible outcomes and adaptation interventions in collaboration with stakeholders. BNs therefore, provide many advantages to studies of climate change and malaria risk, however, their application is limited in the same, partly due to the transdisciplinary modelling process which requires stakeholder involvement and partly due to the lack of a defined process.

Here, we advance previous work to develop a BN model of factors influencing malaria risk in a highland community in East Africa. We start with an established integrated risk assessment framework that identified and ranked key biophysical and socio-economic factors influencing malaria risk in the community and we apply further simplification criteria to reduce the system to a parsimonious set of 15 key variables used to develop a hybrid BN model. We parametrise the BN model using a variety of multi-disciplinary quantitative and qualitative belief data. We use the BN model to provide robust estimates of climate change and malaria risk based on climate, climate change and other environmental, socio-economic and socio-cultural factors influencing malaria risk in the community. We additionally run predictive analyses to estimate the posterior probability of risk of malaria infection given conditional prior probabilities under different scenarios to suggest potential adaptation options for policy-makers to manage risk of malaria infection at the community level.

Keywords: *Integrated modelling, climate change and malaria risk, systems thinking, Bayesian networks*

An integrated approach for improved management of an island's scarce water resources under climate change and tourism development

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Abstract: The management of island water systems in highly developed tourism destinations of developing countries presents many challenges in the face of climate change. Such systems are high levels of uncertainty and complexity driven by dynamic interactions amongst multiple climatic and non-climatic drivers with many feedbacks. Understanding complex interactions and feedbacks in the systems is, therefore, critical to develop a long-term strategy for safeguarding a growing water demand from socio-economic development. In this study, an integrated approach was applied to improved management of scarce water resources in Cat Ba Island under high levels of climate change and socio-economic stressors. Specifically, a range of relevant historical data was collected and examined to identify interrelations among climatic and non-climatic drivers on the island water resources. In addition, 961 households in six communes and one town in the Cat Ba Island were interviewed to understand respondents' perspectives on threats and adaptation options for the management of the island's scarce water system. Results of relevant historical data analysis and respondents' perspectives were used together with focus group discussions to develop a causal loop diagram (CLD) for the Cat Ba Island's scarce water resource system under high levels of climate change and tourism development.

The CLD provides a comprehensive representation of the island's scarce water resources driven by multiple relationships and interactions amongst climatic and non-climatic drivers as well as adaptation options, represented by two reinforcing loops (R1 and R2), and ten balancing loops (B1 to B10). These loops provide further information on the potential water scarcity in the island in both current and future conditions. Specifically, water demand has been observed to be significantly increased over time due to high levels of population growth and tourism development, depicted by two reinforcing loops (R1 and R2). However, water supply has been decreasing over time due to sea level rise and precipitation decline. These observations are represented by ten balancing loops (B1 to B10) in which seven balancing loops (B4 to B10) represent a "Drifting goals" system archetype to seek the stability in water availability in the system.

The next stage of this study is to apply a system dynamics model (SDM) to assess the vulnerability of the island water system in 47 years, from 2014 to 2050 under climatic and non-climatic changes. Simulations targets the year 2050 because it provides a long-term perspective from which the long-term dynamic behaviour of the island water system and the consequences of the plausible future scenarios could be assessed to inform adaptation decision-making. The key climatic and non-climatic drivers and adaptation options from the CLD will be incorporated into the SDM to assess the vulnerability of the island water system and effectiveness of adaptation options under climate change and socio-economic stressors over time. The SDM will be calibrated using relevant historical data, and validated by local stakeholders for decision-making supports. A contingent evaluation method is also applied to examine the determinant factors influencing respondents' willingness to pay (WTP) for building reservoirs and increasing water price for improved management of scarce water resources in a highly developed tourism island under climate change. The logistic regression models and Bayesian networks will be used to identify determinants of the respondents' WTP for the management of the island's scarce water system. The results of this study will assist decision-makers and water managers to understand dynamics behaviour of the system over time, and respondents' perceptions, thereby applying more effective practices to the management of scarce water resources under high levels of climate change and tourism development in the Cat Ba Island, Vietnam.

Keywords: *Community perceptions, climate change, socio-economic stressors, island scarce water resources, systems thinking approach*

EXTENDED ABSTRACT ONLY

Probabilistic predictions of coastal erosion: Spatial Bayesian Network

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Abstract: In this paper, an integrated approach combining Bayesian network (BN) with GIS is proposed for making a probabilistic prediction of coastal erosion and assessing the implications of adaptation measures, which may affect the interactions and trade-offs between diverse ecosystems services. A BN - a probabilistic graphical model - is developed to define the components of a coastal system and their causal relationships. The BN has a capability of using a range of qualitative and quantitative information into a single probabilistic model while GIS explicitly deal with spatial data for inputting, storing, analysing and mapping. The proposed integration of the BN with GIS using a cell-by-cell comparison technique (aka map algebra) provides a new tool to perform the probabilistic spatial analysis. To put this approach into context, a case study of Tanna Island in Vanuatu in the South Pacific is investigated. Based on the BN model, the rate of the island shoreline change is predicted by updating the probability of the coastal erosion rate. The most likely case with the highest probability is then selected as its prediction for the case of shoreline segment. Then, probability maps are created by transferring the results of BN back into GIS. In this way, the spatial distribution of prediction results for the island's shoreline change was mapped. Finally, spatial variation in the implications of the adaptation measures on the provisioning of ecosystem services is assessed.

Keywords: *Spatial Bayesian network, probabilistic coastal hazard mapping, climate change risk, probabilistic risk mapping*

Assessment of tree shade coverage in forecasting seasonal energy saving of houses

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Abstract: Designers of energy-efficient dwellings in Australia have taken initiatives to improve the thermal performance of building shells and consequently have less thermal energy consumption from electrical indoor air conditioners. The thermal response of the houses to local climate conditions is ranked based on hourly heating and cooling energy requirements over a typical meteorological year. The higher-rated houses in Adelaide reduced energy consumption by 19% in winter and statistically showed the same energy usage in summer compared to traditional houses (less than 4-star rating out of 10) (CSIRO 2013). The detailed quantitative weather data can assist the development of a tool to optimise energy consumption in houses. This paper focuses on how trees as a well-known natural climate modifier (Norton et al. 2015) can affect the thermal energy performance of dwellings.

Three phases of methodology were applied using mathematical modelling, field measurement and computer simulation to analyse the dynamic interaction between the microclimate and the building. This paper developed mathematical approaches to provide interdependent weather data. These data include local ambient temperature and global solar radiation on vertical surfaces to understand the correlation between them and their impacts on seasonal analysis of a 7.5-star house in the whole year. Field measurement was conducted in 11 different locations in Adelaide to measure local microclimates on the different types of tree shading coverage compared to the situation without trees. Hourly air temperatures at 1.5 m height were monitored under tree crowns having partial and full shading conditions in a one-year experimental period. New meteorological weather data is calculated based on the statistical modellings and the experimental settings. The weather data has been processed and adjusted on a seasonal basis which is embedded in AccuRate engine to predict the thermal energy consumptions.

The seasonal and annual energy consumptions were investigated under the partial/full tree shade coverage in both daytime and night time. The results reveal the annual heating thermal energy decreases by 30% in winter and 77% in autumn in both day and night because of trapping longwave radiations and keeping the ambient temperature higher in those seasons. The annual cooling thermal energy also reduces by 60% in spring and 4% in summer, with 8% less night time usage than the day. All investigations were compared with the heating and cooling thermal energy loads without trees. Even though 4% reduction in summer is not great, however, it must be remembered that the higher-rated houses showed the same energy consumption as the traditional houses for cooling. So, reducing that load further, even though only slightly, is a positive result. In Adelaide climate zone, the total energy consumptions in both spring and autumn significantly less than summer and winter. Therefore, 60-77% reduction shows almost two months without air conditioning in spring and autumn which leads to annual energy saving by 5-6.5%. The seasonal heating and cooling usages indicate that thermal energy performance of the houses depends on ambient temperature which is affected by both 2-hour previous solar radiations and tree shading coverage. As a result, optimization of tree planting strategy is essentially needed to enhance energy performance of the higher-rated houses (more than 6-star rating) or even traditional houses (less than 4-star rating out of 10). It is clear that this effect should be much more significant in traditional houses.

Keywords: *Energy-efficient house, tree, natural climate modifier, Seasonal energy consumptions, AccuRate*

Orienting solar panels to minimise power shortfall

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Abstract: Solar panels on residential dwellings are typically installed facing the equator to maximise the energy collected. But the power generated by an equator-facing panel peaks at around midday, whereas residential loads typically have peaks in the morning and afternoon. By orienting panels in different directions it is possible to minimise the shortfall between load and generation. This benefits the end-user by decreasing the amount of electricity required to be imported, and the stability of the grid by decreasing the amount of variability between peak and low loads. We present a linear program for calculating the optimal panel orientations for a community of 29 individual dwellings, and for an apartment building with 42 apartments in Australia. In both cases, panels should initially be placed facing north-west to meet the afternoon loads. If more panel area is available, the optimal configuration has fewer panels facing north-west and more facing north-east and west.

This information has been used by a developer to design a renewable energy system for a retirement village.

Keywords: *Solar energy, aggregating demand, embedded network, optimisation*

System dynamics based interactive game for managing the looming rooftop solar and battery waste crises in Australia

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Abstract: The exponential uptake of rooftop solar is causing a concern on the looming e-waste crisis once the technologies reach the end-of-life. Solar panels and battery energy storage make up the major components of rooftop solar photovoltaic systems. The underpinning valuable and critical materials present in both solar panels and batteries, the recovery process is imperative to conserve and recirculate these materials to meet the future demand of solar energy systems. This research aims to develop a participatory systems model to examine different transition pathways towards an effective end-of-life management system of residential solar photovoltaic and battery energy storage in Australia. This project is divided into five stages: 1) problem scoping, 2) conceptual model development, 3) system dynamics model development, 4) scenario analysis, and 5) serious gaming development.

Firstly, a systematic literature review approach was used to identify knowledge gaps as well as to synthesise the list of drivers, barriers, and enablers. Secondly, the list was validated through an iterative expert review process regarding its comprehensiveness, relevance, and clarity. A stakeholder survey was then utilised to compare the drivers, barriers, and enablers among stakeholders. The second stage involved the development of a causal loop diagram based on the results of the previous stages and was validated via two stakeholder workshops to ensure its validity. The causal loop diagram captured the complexity and causal feedbacks between variables underpinning the studied system. The diagram is divided into three themes: 1) waste generation, collection, and disposal; 2) end-of-life management strategies; and 3) cost and benefit analysis.

Based on the conceptual model, a system dynamics model will be developed and will be refined and validated via a stakeholder workshop. The model will then be used to examine different transition pathways toward an effective end-of-life management system. In the latter stage, the system dynamics model will be linked to an interactive role-play gaming platform. This game will be presented in a stakeholder workshop which enable stakeholders to change and response to different strategies. This stage is imperative to facilitate stakeholder learning process regarding the long-term and medium implications of various policy or parameter adjustments. The implication of this research project is to assist policy makers and industries to find an optimal strategy towards an effective management of end-of-life rooftop solar and batteries in Australia.

Keywords: *Solar photovoltaic, battery energy storage, system dynamics, product stewardship, Australia*

Water and energy-based optimisation of a "MiniCity": A system dynamics approach

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Abstract: Urban sprawls in Australia and several countries around the world have introduced a number of social, economic, and environmental issues for residents and urban planners, highlighting the need for new urban development concepts.

In recent years, the concept of a vertical sprawl called "MiniCity" has been presented. The objective of a successful "MiniCity", compared to traditional high-rises, is to be as self-sufficient and self-contained as possible; whilst also minimising issues such as car dependency, loss of agricultural land and natural habitats, water and air pollution, and poorer health and wellbeing, which are common for residents in low-density, low-rise areas and developments. To date however, the viability of a MiniCity has yet to be properly addressed.

Arguably, the predominant needs for a community are water, energy and food. In this research study, a System Dynamics model was developed to simulate supply and demand of the water and energy systems, as well as their interaction, for a hypothetical MiniCity located in South-East Queensland, Australia. The models were conceptualised based on expert knowledge, with data and equations collected from local Gold Coast sources and from the literature. Preliminary results show the complex, but expected, dynamics and interactions between the two systems, and their dependence to critical input parameters, such as climate data, roof area, number of floors, to name a few. Future work will focus on adding other critical modelling components such as food production and thus analyse the water-energy-food nexus.

The final, validated model will allow the optimisation of critical MiniCity parameters and the identification of suitable locations that can maximise the socio-economic and environmental viability of the MiniCity.

Keywords: *MiniCity, systems modelling, urban planning, water-energy nexus*

Using instructional design theories to incorporate motivational elements into simulation design: application of the ARCS Framework

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Abstract: Modelling and simulation is a useful approach in understanding and dealing with complexity, but often struggle to persuade users. One potential reason for this shortfall may be that limitations in development of the interface design do not optimize human learning with the model.

Techniques to improve information transfer and learning have been extensively studied in education literature. Yet, much of this instructional design theories and methods have not been transferred to or leveraged in the field of modeling and decision support systems. Development of modelling and simulation systems do not systemically include psychological factors design to persuade and influence humans in the same way that instructional design methodologies do. As instructional design focuses on identifying, tailoring, developing and analyzing material to impart knowledge to a student, those practices are inherently focused on the response of people to the information and methods used.

One theoretical framework in the field of instructional design is the ARCS (Attention, Relevance, Confidence, Satisfaction) approach, which aims to provide a systematic design approach to pedagogy to improve learner's motivation. The ARCS framework covers strategies within each of the four main areas as well as several recommended implementation tactics within each of these four main strategies. The systematic and theoretically based design has the potential to improve people's ability to learn by increasing their willingness to engage with material and to revise mental models. The ARCS framework has several accompanying surveys that have been validated as tools for understanding and assessing the effectiveness of learning activities against the ARCS framework, such as the Instructional Materials Motivation Survey.

The opportunity exists to explore if structured design of the human-model interface using ARCS principles will improve a users' ability to interact with complexity and enhance the learning outcomes achieved through the interaction. If instructional design principles improve the human-model interface, then the potential exists for modelling and simulation practice to leverage of well-established educational frameworks and bodies of knowledge in order to enhance modelling practice.

This pilot case study explored how the ARCS Model of Motivational Design can be used to enhance simulation development. We developed a life-simulation of a workplace environment that replaces a one-week technical module of an existing twenty-six week vocational course with a representative project team environment based on the future employment conditions of the students. In doing so, it will seek to develop practical job skills in parallel with the teaching of technical information in a specific engineering area of practice.

The case study aims to address two main questions. how can the ARCS framework be implemented in development of a simulation? Secondly, can the ARCS designed simulation blend learning of workplace skills in addition to technical knowledge, increasing the material absorbed in the time allocated?

Exploring the feasibility of using motivational design to develop a simulated workplace environment will investigate how the deliberate inclusion of ARCS techniques affects motivation to learn. Lessons learned in application of ARCS to simulation development will feed into future experiments on the relationship of motivation and user engagement with the simulation models.

Keywords: *Stakeholders, motivation, ARCS*

Studying behaviour in operations research interventions: A 30 year review

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Abstract: When we focus on action in participatory environmental modelling it is important to understand what are the possible behavioural effects that can be present and have an impact on the outcome of the process. For this purpose a review of research findings related to behaviour in modelling interventions can provide useful insights for taking behavioural effects into account when taking modelling outcomes into action. This paper maps the rapidly growing body of empirical research that examines behaviour in operations research (OR) interventions. Phenomena found in OR interventions are likely to be present also in participatory modelling in general. We surveyed the relevant literature over a 30-year period and develop a typology of four distinct approaches to the study of behaviour in OR interventions, see Table 1. Each approach varies in how it characterises behaviour (*directed* or *adaptive*), and the research methods it uses to conduct the study (*variance* or *process*). Each approach has differences and similarities, as well as strengths and weaknesses, in addressing various research questions about behaviour in OR interventions. It is worth noting that the interventions so defined can take place either in the lab or the field. We argue that each approach can only offer a partial understanding of the role and impact of behaviour in OR interventions. However, taking the insights produced by all four approaches together offers a richer understanding of the behavioural dimension than any one approach can offer by itself. In this review we use the term 'intervention' to refer to an active and deliberate effort by one or more actors to engage with an OR-supported process intended to address some problem or problematic situation of interest. This framework is also directly applicable to studies on participatory modeling too.

Table 1. Typology of approaches to the study of behaviour in OR interventions

		Behaviour	
		Directed	**Adaptive**
Research method	**Variance**	**Approach I** Variance studies of the impact of OR intervention on actor behaviour, *including that caused by the cognitive processes or individual traits triggered by the intervention.*	**Approach IV** Variance studies of the impact of actor behaviour on OR intervention, *either through self-adaptive behaviour to comply or wilful action to change the intervention.*
	Process	**Approach II** Process studies of the impact of OR intervention on actor behaviour, *including that caused by the cognitive processes or individual traits triggered by the intervention.*	**Approach III** Process studies of the impact of actor behaviour on OR intervention, *either through self-adaptive behaviour to comply or willful action to change the intervention.*

We cover papers published between 1987 and 2017 in ten selected journals: *European Journal of Operational Research*, *Operations Research*, *Management Science*, *Omega, Journal of the Operational Research Society*, *Decision Support Systems*, *Group Decision and Negotiation*, *Systems Research and Behavioural Science*, *Decision Analysis*, and *System Dynamics Review*. Clearly, relevant papers can be found outside our selected group of journals. The results of the review include e.g.: The total number of empirical studies found and the number of studies in each cell; The proportion of studies from facilitated vs self-facilitated vs non-facilitated OR; Time trend of the publication of the studies; Average number of citations for the papers. We also provide characterizations of typical findings in each cell.

Keywords: *Behavioural OR , Participatory modelling, modelling, intervention*

Persuasion, influence, and participatory modelling in socio-ecological systems: A framework for action

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Abstract: Practitioners studying socio-ecological systems (SES) often struggle to 'persuade' stakeholders to transform knowledge arising from the scientific modeling process into meaningful changes in behaviour. Participatory modelling (PM) aims to address this problem by engaging stakeholders of a given problem in the process of co-creating knowledge, making decisions, and ultimately converging towards collaborative solutions informed by science. While the effectiveness of PM is well documented, the process of building participatory models could learn from and improve with the aid of behavioural science. Behavioural science studies how humans actually make decisions and act, providing practical knowledge to steer people toward decisions that improve long-term welfare. By applying behavioural science to PM, scientists can position themselves as influencers for ideas and practices that actually improve the systems they study. In turn, it can also help stakeholders by 'priming' them to both understand and to implement practices that improve long-term individual and collective outcomes.

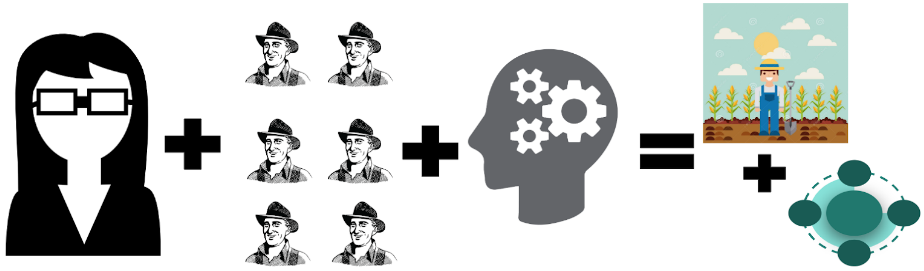

Figure 1. The Benefits of Applying Behavioural Science to PM

This paper describes a diagnostic questionnaire, drawing from the Theory of Planned Behaviour (TPB), that can underlie and improve a PM exercise by 'mapping' where stakeholders sit in regards to an idea or practice. TPB states that behaviour can best be predicted by three central concepts: subjective norms (social networks), perceived behavioural control (power), and attitudes (personal). The diagnostic questionnaire examines these three elements to determine which drive stakeholder actions. When combined with other theories from behavioral science, this diagnosis can then lead to a toolkit that experts draw upon during a PM exercise. Such a toolkit helps experts better account for the decision-making processes of their stakeholders. It also assists in choosing more effective ways to deliver their messaging to increase stakeholder understanding, and to improve the likelihood of stakeholders adopting any collectively agreed upon actions.

To test this diagnostic tool, I focus on farmers, as their relationships with the land, the markets, and the services they supply are the archetypal example of a complex, inter-woven SES, in pressing need of change. First, I interview experts in charge of managing the Mulloon Institute near Bungendore, NSW to assess what factors are crucial to changing farmer behaviour, the boundaries of their decision-making, and whether or not my questionnaire captures the main factors influencing behaviour change. These experts include farmers, community leaders, and government officials. With this data to support and update the questionnaire, I will then proceed to a PM exercise, using the diagnostic questionnaire to assess what drives stakeholders of Mulloon towards or against regenerative agricultural practices. While this case study focuses on Australian agriculture, findings of this research should be relevant to other socio-ecological systems where natural capital is deteriorating and human behavior is a key driver of system performance, such as agriculture, fisheries, mining, forestry, and the management of water resources.

Keywords: *Participatory modelling, influence, behavioural science, agriculture*

Ecological vs social thresholds for use in modelling

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Abstract: Ecological models are tasked with an increasingly difficult job as the uncertain impacts of climate change and the effects of human disturbance can compound to cause swift change in ecological systems, drastically altering natural habitats and decimating vulnerable species. When targeting a specific species or ecological element of concern, these models help us understand and visualize the life cycle of a population and identify specific points of intervention. The concept of ecological thresholds has gained hold as a potentially powerful concept that, combined with strategic environmental monitoring programs, could contribute to robust adaptive management plans. The concept of ecological thresholds is used to represent a rapid transition between ecological states in a system after which point the original state cannot be restored. In a management context this idea is often used to communicate that there is a level of ecological degradation past which rehabilitation cannot take place without extreme difficulty.

While ecological thresholds and tipping points can become the basis for conservation management, several factors make them difficult to implement. Firstly, there is no agreed upon definition of an ecological threshold. The context specific nature of ecologically thresholds makes them difficult to translate between different populations or between regions. Additionally, expert derived ecological thresholds often fail to account for complex socioeconomic variables that influence public perception. This oversight can lead to a lack of wider community support and stall management plans. These shortcomings make these thresholds an inefficient management tool.

This project includes a case study examining a method for determining socially derived ecological thresholds during a participatory modelling process. This project takes place in the context of an environmental flows assessment for the Goulburn-Broken catchment in Northern Victoria, Australia. Participatory modelling is a well-suited vehicle for exploring the question of socially determined thresholds. Carefully facilitated workshops and a collaborative learning environment encourage participants to think critically about their catchment. During the workshops there was a discussion of management objectives for the catchment, including a conversation about what catchment conditions would be unacceptable. Unacceptable outcomes may be related to ecological objectives but are considered within the socio-economic context of the catchment. These conversations inform what thresholds will be incorporated into the quantitative models developed for the flows assessment. We will report on what social thresholds have been determined by the participant group and explore the importance of these thresholds within the context of the catchment. These thresholds will be contrasted with possible ecological thresholds determined with the aid of an expert panel. We will then explore the potential for incorporating these thresholds into ecological models.

Using socially determined thresholds for modelling practice and ultimately decision making in water resource management addresses some of the inadequacies of ecological thresholds. It responds to the need for conservation strategies to be more holistic and address the concerns of the communities where management takes place, building community support and ultimately increasing the chances of successful management.

Keywords: *Threshold, natural resource management, decision making, socio-ecological system*

How wicked are wicked problems and how do we model them

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Abstract: The concept of 'wicked problems' has emerged more than 50 years ago, and has been later on explored in numerous publications and applications, and produced further theories such as the post-normal science concept. All the policy and planning problems in pluralistic societies have been identified as wicked, which means that they cannot be properly defined, cannot have any single solution, moreover, they cannot have any correct or false solutions at all. Systems modelling, especially participatory modelling have been proposed as useful tools to use when dealing with wicked problems. Attempts to address the 'wickedness' also gave rise to justifying further increases in complexity of models that are built.

While being a stimulating philosophical concept, the idea that certain problems simply cannot have solutions creates some forms of escapism that may justify inaction. The same we see in how uncertainty is being repeatedly used to avoid making decisions. In reality most of wickedness may be a product of wrongly identified system boundaries and lack of understanding of hierarchies involved. We find that in much too many cases we tend to ignore the elephant in the room, trying not to look at the system at other scales, where the solution is more obvious, but may be contrary to the preferences and values of some stakeholders. We make problems wicked when we assume that only win-win solutions are acceptable, or when we try to make only popular decisions. The idea of unsolvable wicked problems is a natural outcome of mature democratic societies that bear the promise of engaging the society in decision making and delivering results that are acceptable for the majority. However, majority changes from local to regional and global scales. While certain decisions may be obviously beneficial in the global scale, they will be unpopular in the local ones. While we have effective democratic mechanisms for local and regional scales, we have almost none in the global level.

Yet there are looming crises in regional and global scales where our attempts to apply the same pluralistic and democratic mechanisms are clearly failing. Participatory modelling which is normally seen as an efficient tool for democratic decision making is not well suited for large scale systems, which involve thousands and millions (or billions) or stakeholders, possibly across cultures. We need to urgently reconsider some of our decision-making procedures choosing between:

1. Accepting that democracy may not be effective in critical situations that involve several hierarchical levels and require fast and effective decision making. In this case a more top-down approach involving experts and fiat will be needed, with models also developed to suit such processes;
2. Using modern communication tools (social media, peer-to-peer computing, MOOCs, etc.) to create massive bottom-up platforms and mechanisms for decision making based of social engagement and learning. This will also expect new levels of commitment from the society to education and social responsibility, and will require different types of modelling tools, which will be scalable, simple to use, communicate and analyse.

Keywords: *Decision making, communication, top-down, bottom-up, hierarchy, scaling, participatory modelling*

Understanding resilience in apple supply chains

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Abstract: As agricultural regions experience unprecedented change in growing conditions and/or increased extreme events with both positive and negative impacts on production systems, we seek to develop a scalable method for the analysis of the agricultural supply chains that provides insight at industry, region or business scales to assess resilience and focus adaptive practices. The method developed was tested against both historical supply chain disruptions and future scenarios based on both observed climate change trajectories and future climate change scenarios.

We focused on the New Zealand apple industry as an exemplar system, which provides a diverse, high value, export-driven supply chain. The New Zealand industry is experiencing ongoing growth both in planted area (~9,500 ha) and value (~$730M in export earnings in 2018). There are about 950 export orchards, 60 packhouses and 80 exporters who jointly produce and ship some 380,000 tonnes of fresh product to 65 countries. Resilience was examined based on the Supply Chain Index (SCI) methodology and using broader network theory we examined how the described network could be viewed from different perspectives to provide more forensic sub- network analysis.

Through targeted interviews with stakeholders from industry both individual business value chains and industry- wide value chains were described, initially qualitatively, but where possible quantitatively. A directed network view was developed based on the flow of produce through the supply chain. Risks to the flow of goods were associated with each element in the chain and used to modify the expected supply and movement of apples based on the risks associated with each major production region.

The industry wide network described a number of distinct operating models each able to withstand system shocks in different ways. Success at the farm gate was dependent on profitability on-farm and the ability of the farm to withstand quite large shocks year on year. Vertically integrated businesses have adopted very distinctly different approaches to dealing with variability, from regional and varietal diversity to the use of a very high value, single variety within a tightly controlled production environment.

Although each of the apple supply chains analysed here deal with climate and market disruptions by implementing and adapting adequate operating models, it is also instructive to assess the effect of these disruptions on the network's resilience and performance along a time period. To that end, we set up a Monte Carlo method where the network model, which incorporates the carry-on effect of disruptions on network performance year after year, was run for a time horizon and each disruptive scenario was assigned a probability. The results from applying the method reveal the dynamics of resilience, as opposed to the static model. The most vulnerable chain components in changing economic and natural environments may not necessarily be the least resilient.

Keywords: *Apple supply chain, resilience, New Zealand, Monte Carlo*

Urban sensing and Weather Prediction: Can IOT devices be used to improve weather prediction in cities?

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Abstract: Data assimilation (DA) in numerical weather prediction (NWP) has relied on observations sourced from variety of sources like radiosondes, dropwindsondes, meteorological sensors and remote sensing through satellites. The sensors used for collecting meteorological variables such as wind speed, wind direction, tem-perature, relative humidity are designed to provide high quality observations. Additionally, a set of defined instructions must be followed for installation of such systems, with the presumption that the sensors will behave as defined in the user m anual. Due to the aforementioned r easons, fi rstly, these systems are expen-sive to install and operate, and secondly, they cannot be installed at a large scale within cities, thus requiring alternative ways of sensing environmental conditions within such areas.

In recent times, Internet of Things (IOT), Big Data and Cloud computing has been attracting considerable attention. This has been made possible by the availability of high speed connectivity, ease of access to high quality computing resources at pay-per-use basis and the increased emphasis on informed decision making. Due to such developments, there has been increased diffusion of smart systems equipped with miniaturized sensors allowing such systems to adapt to their environmental conditions *e.g.*, smart air-conditioners control-ling the indoor conditions in response to the changing ambient environment. These disruptive technologies have led to the development of platforms such as Tulip[1], Array of Things[2] and Dryp[3], that rely on alternative sensing methods and technologies.

Historically, weather and climate predictions has been carried out by the national weather agencies. These agencies use weather models together with the data from their observation networks to provide weather fore-casts for public use on time scales ranging from daily, yearly to decadal. Despite the considerable advance-ments in modelling and computing systems, the weather forecasts from agencies can only attain spatial res-olution of 1-10km. Due to the cost and computational systems needed to run such models, there has been a growing interest in combining big data and machine learning to aid in localizing the predictions performed by these models.

In the current study, we investigate the implications of combining observations from Array of Things (Catlett et al., 2017) network installed in City of Chicago with the model outputs from Conformal Cubic Atmosphere Model (CCAM). To that end, the study utilizes modelled and observed air temperature over a one month period. The preliminary results showed a good correlation between the modelled and observed air temperature. However, the sensors mounted on AOT node use different sensing techniques to measure air temperature. Due to these differences, a considerable spread exists in the air temperature observed by the different sensors mounted on a single AOT node. This observed spread in the air temperature underlines the need of caution when using data from IOT devices. Further evaluation against the data from a co-located meteorological sensor may elucidate the implications of this spread when data from IOT devices is combined with the models.

[1] https://www.tulipnetwork.org
[2] https://arrayofthings.github.io/
[3] https://www.dryp.global

Keywords: *Numerical weather prediction, Internet of things, Array of things, Bias correction*

Rainfall retrieval using commercial microwave links in Melbourne, Australia

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Abstract: Rainfall remains one of the most challenging meteorological variables to measure accurately. Dense rain gauge networks combined with operational weather radars are widely used as reliable sources of temporal and spatial rainfall estimates. However, deploying such observation systems is costly. Furthermore, rain gauges only provide discrete point observations, and radar rainfall products are prone to large uncertainties due to calibration, ground clutter and anomalous propagation. Fortunately, there are dense networks of commercial microwave links, which can provide untapped resources at an intermediate scale between point measurements from rain gauges and weather radar volume resolutions. The primary objective of such commercial microwave links is to provide point-to-point wireless communication using high-frequency radio waves between 1 GHz – 100 GHz. The transmitting signal in those links suffers an attenuation when it passes through the rain medium, which is recorded by all the telecommunication operators as the regular quality monitoring of their work. This signal attenuation can later be inverted to the rainfall using the well-known power relationship between attenuation and rainfall. This opportunistic sensing has already been demonstrated to be a complementary technique of rainfall estimation around the world. The major advantage of link-derived rainfall estimates is that they provide path-integrated measurement of rainfall close to the ground.

In this study, we present the first evaluation study of rainfall retrieval using commercial microwave link data for the Melbourne, Australia using two years (July 2017- June 2019) of received signal level data collected from 144 microwave links (recorded at 15-minutes interval with minimum, maximum and average sampling strategy). Rainfall intensities for all links are validated with the path-average rainfall intensities obtained from the gauge-adjusted radar product and automatic rain gauges. Results showed the correlation above 0.40 between the observed and link derived rainfall for 15-minute time step and this increases to 0.80 when compared with 1-hour time step. We also compared the results between two sampling strategies (Minimum/maximum and average). Comparison of our results showed that average outperforms minimum/maximum sampling regarding the quantity of rainfall at a 15-minutes sampling rate for the Melbourne climate. Minimum/maximum sampling performs better for the dry-wet classification generating less false alarm ratio than average data. Thus combining results from minimum/maximum and average sampling strategies helps to improve the overall rainfall retrieval using microwave links.

Keywords: *Rainfall, commercial microwave links, sampling strategies, received signal levels*

Understanding mental models through a moderated framework for serious discussion

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Abstract: Mental models are informal representations of how the world works. They influence how we perceive, behave, and decide. Mental models are updated and maintained through direct observation, learning, and experience, and are continuously relied upon to reason, explain, design, communicate, act, predict, and explore. As such, they play a fundamental role across all areas of human agency. Practitioners from fields as diverse as behavioural science, psychology, economics, education and sustainability would therefore gain much insight from tools that enabled them formalise computer simulations from the mental models expressed by a group within a given problem situation.

Our goal is to develop a real-time, moderated steering environment for better understanding and formalising mental models from online discussions. Users are presented with a topic, question, or problem to debate, on which they can express their opinions/thoughts in the form of comments. Users can also respond or expand on other user's opinions and/or initiate a new line of discussion. The discussion chain is then mined in real time, using an ensemble of algorithms (including but not limited to concept mining, topic modelling, and sentiment analysis) to extract opinions, keywords and concepts. This information is transcribed into semi-quantitative simulations using Fuzzy Cognitive Maps, Causal Loop Diagrams, and Networks Diagrams as the discussion evolves (Figure 1). To provide feedback, the system presents users with dynamic visualizations of the collective mental model which they can use as contextual information to refine and update their individual mental models. Feedback can also be introduced by targeted moderator comments to steer or "nudge" the discussion towards a desirable collective mental model, outcome, consensus, or agreement.

This framework could be used in a variety of settings and problem situations where the steering of collective mental models could improve the functioning, resilience and/or sustainability of a given (social, environmental, or technical) system, or used by policy makers or any other organization who would benefit from a more direct, transparent and meaningful engagement of its stakeholders.

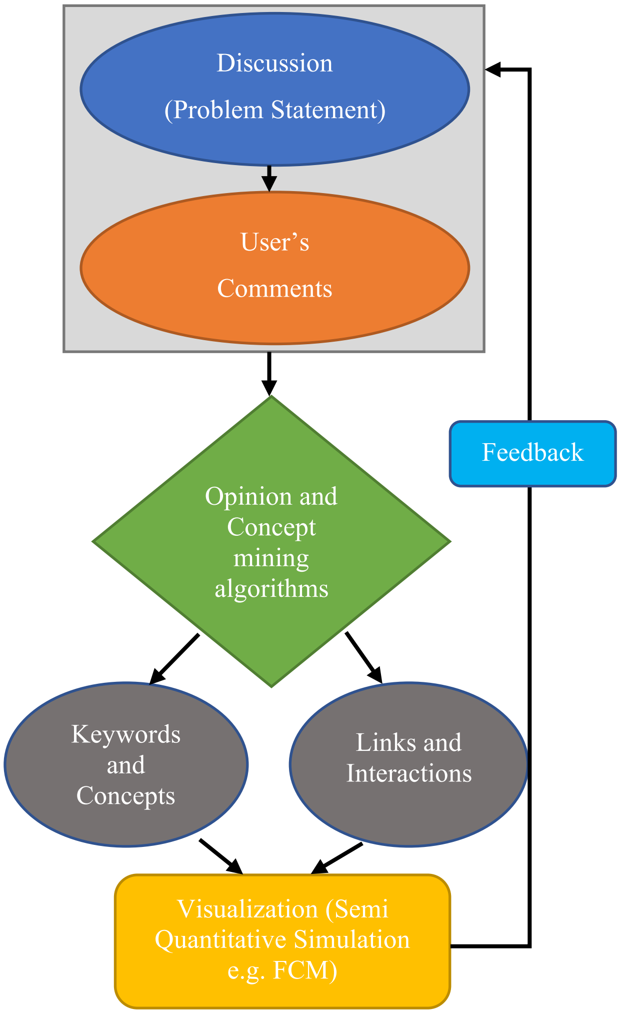

Figure 1. Overview of Framework

Keywords: *Real-time steering environment, moderated serious discussions, social feedback*

Gamification of participatory modeling in the context of sustainable development: existing and new solutions

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Abstract: Serious games and gamification tools have gradually expanded their application in participatory settings, while already being widely used in the context of sustainable development in general. Their popularity is explained by their ability to create an engaging and experimental environment, which evokes critical thought, meaningful interaction between the participants and experience-based learning.

Although game design principles and tools are, to a large extent, universal, their application differs from one field to another. The simulation modelling field has a long history of using game elements to make complicated models more user-friendly and understandable for wider audiences. Management flight simulators, microworlds, policy exercises and strategic simulations are among the most common examples. Meanwhile, the urban planning field often makes use of interactive 3D maps, including the most recent advancements in applying XR technologies to make the interaction with the system more tactile and collaborative in a multi-user setting. Serious games are used in participatory projects as a supplementary approach to provoking discussion among the stakeholders and stimulating critical thinking. Gamification in the participatory modeling field is commonly used at the initial and final stages of the process or by incorporating a role playing component into the process (e.g. in companion modeling and social simulations). Based on the existing research, we have two main observations: (1) in each of the above-mentioned fields there are traditional ways of using gamification and visualization instruments and there is a lack of 'cross-pollination' between various application fields in terms of choosing gamification tools, (2) gamification tools are commonly used at one or two stages of participatory modeling process but rarely over the entire process of participatory modeling. We suggest that by introducing more gamification elements throughout the whole PM process we can produce a more gameful or, at least, a more engaging experience for stakeholders.

As a preliminary step towards wider use of gamification in the participatory modeling process, we first analyze how existing gaming solutions from various fields can be applied in the context of different stages of participatory modeling. In our research we critically reviewed the use of gamification from two perspectives: (1) to which extent it could help to mitigate the challenges of participatory modeling process (e.g. biases, groupthink, conflicts, etc.) and consequently contribute to better learning and communication between the participants, (2) how it could contribute to the creation of engaging experiences for the participants during participatory modeling process. As a result, we propose a framework for gamification of each stage of the participatory modeling process taking into consideration the already existing solutions, as well as the insights from the game design and behavioral science fields.

Keywords: *Modeling with stakeholders, serious game, stakeholders' participation, sustainability*

EXTENDED ABSTRACT ONLY

Model-enabled community engagement in a mining approval process

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Abstract: Participatory Modelling (PM) can help regulators and communities move toward more positive futures by making stakeholder engagement more meaningful, efficient, and informative (Sterling et al, 2019). We are partnering with industry and agency groups to drive two major innovations in this space: (1) developing a standardised, web-enabled reporting structure for PM processes, and (2) using "management flight simulators". We are developing these tools to provide an objective, transparent and flexible process where a diverse group of stakeholders can rapidly understand and meaningfully contribute their local knowledge to an early-stage mining or energy development proposals.

There are many types and variations of PM, and their value has been amply demonstrated in natural resource management and protection contexts (Voinov et al, 2018). One of the difficulties limiting a wider adoption of PM is the lack of consistent reporting about the engagement processes to enable others to avoid pitfalls and replicate successes (Glynn et al, 2017). This issue led Glynn et al (2018) to call for a new type of record to document PM processes and outcomes, which they term Records of Engagement (RoE).

We are responding to this challenge within an important real-world application, through which we explore how tools such as discourse analysis, mental model maps and data visualisation can be combined to create RoEs that capture and communicate the complex information and relationships uncovered during a given PM case-study. Using the experience gathered in this application, we will develop an adaptable RoE template and guidelines to encourage the adoption of RoEs in future collaborative modelling projects.

Effective and useful RoE's require an electronic and highly adaptable format, and creatively apply information visualisation tools to communicate complex information, trends and ideas. Fundamental beliefs of the stakeholders and engagement leaders such as their world view, knowledge about the subject, personal values, heuristics and potential biases will be measured, anonymised and reported to unlock understandings about the engagement results. One Bayesian aspect which we are exploring is stakeholder's willingness to change their minds when new information is presented. These aspects will be measured through progressive surveys, structured interviews and analysis of stakeholder communications as the engagement process unfolds.

The other major innovation in this project is to apply PM in an Australian development planning approval context. A major perceived shortcoming of current planning approval processes in Australia is the lack of meaningful stakeholder engagement beyond invitations to submit written comments once the Environmental Impact Statement has been published (Walsh et al, 2016). We are working with a number of sponsors to address this fundamental issue by applying "management flight simulators" (Castilla-Rho, 2017) and other collaborative modeling tools to enable efficient and effective stakeholder engagement in the scoping phase of a real NSW planning approval process. If successful, the ability to quantify thresholds of concern has potential for transformative improvements in the strength and transparency of approval decision-making. We are therefore designing the engagement framework in this project to become an adaptable prototype to encourage model-enhanced stakeholder engagement in future mining and energy developments.

Keywords: *Participatory modelling, Records of Engagement, stakeholder engagement, planning approval context*

Science for Sustainability: Using Societal Metabolism Analysis to check the robustness of European Union policy narratives in the water, energy and food nexus

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Abstract: This paper is an output of an ongoing EU Horizon 2020 project (MAGIC) that aims to better understand how EU water, food, energy, waste and biodiversity policies link with each other and with EU climate and sustainability goals, framed in terms of the nexus concept. The project conducts transdisciplinary research with policy makers using an approach termed Quantitative Story Telling (QST), as an interface between science and policy domains. QST combines semantic (qualitative) and formal (quantitative) approaches to assess the plausibility, normative fairness and analytical coherence of narratives being used by stakeholders to justify either the *status quo* or alternative policy positions for the EU. The paper focuses on those aspects of the MAGIC analysis highlighted by external reviewers of the project as being most insightful and having the most potential value to a wider community of practice concerned with supporting or evaluating sustainability related policies. The paper outlines the process of QST used and the quantitative method used, multi-scale societal metabolism analyses (SMA) assessing the funds of land and human time needed to create the flows of materials, energy and money that reproduce and maintain the identity of the system of interest.

As one of the five MAGIC policy studies, the authors focused on a key EU Common Agricultural Policy (CAP) narrative. CAP is a policy which is now expected to deliver multiple objectives across policy domains, but as implemented, potentially contributes to a tension between supporting competitiveness and delivering public goods. High-level findings that quantify aspects of this tension are presented, followed by specific technical issues found when conducting the analysis. The paper then reflects on the authors' use of these data to discuss with policy-makers issues where the tension between competitiveness and public goods are most stark; a more interpretive, qualitative phase of analysis that builds on the quantitative analysis.

The outputs of the analysis used within the CAP QST imply the need for policy makers to consider alternative issue framings, otherwise they risk appearing to make only a rhetorical commitment to defining and delivering EU sustainability goals. The societal metabolic framing used in MAGIC highlights the biophysical underpinnings of EU farming systems; their dependence on non-renewable resources and the pressures generated by them that degrade ecosystem functions or services. A societal metabolic framing also means considering multiple scales, since otherwise EU policy is blind to the effects it has on sustainability beyond the borders of the EU.

If research impact is defined in terms of acknowledged change in stakeholders' concepts or behaviours (an expected impact for the project by funders) then to date, there has been limited 'success'. While the rhetoric of 'evidence-based policy' remains prominent, it remains extremely challenging to engage with policy makers in deliberation on evidence that challenges conventional narratives. This was the case even for staff with extensive experience of inter- and transdisciplinary working at the science-policy interface.

In conclusion, science for sustainability policy could benefit from adopting the approaches like QST, which can integrate and balance the semantic and formal parts of science for policy research. For the wider science-policy community of practice, the key insight is that for processes like QST the key decisions are made at the interfaces between the sematic and formal phases of analysis (what is modelled and why) and the formal and semantic phases of analysis (what the outputs mean and why they shouldn't be ignored).

Keywords: *Societal metabolism, sustainability, nexus, science-policy, common agricultural policy*

Building trust in modelling for integrated water management: an inter-institutional example from Uruguay

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Abstract: Hydrological modelling is a key element of integrated water resource management (IWRM) as integrators of knowledge and as tools for scenario modelling. However, due to the inherent complexity of numerical models and the diversity of stakeholders in IWRM, challenges in building trust in model outcomes in IWRM have been well documented. In Uruguay, there has been significant debate about the best way to increase agricultural production while managing agriculture's impact on the environment. Land use change and intensification of agriculture has led to concerns about impacts on water quality and environmental flow. To be able to answer questions around this issue, staff from the Institute of Climate and Society (IRI) and the University of Sydney (USYD) organised a series of workshops to identify solutions and develop capacity in the area of hydrological scenario modelling. As a result of these workshops several Uruguayan government departments combined to develop an inter-institutional modelling group with a two-fold aim: 1) develop capacity in the area of hydrological scenario modelling; 2) develop trusted scenarios for a specific case study catchment (Santa Lucia River sub catchment) which provides the majority of the drinking water for the capital city Montevideo. Apart from staff from the government departments, the pilot group included members of the engineering and agronomy faculties of the National University and staff from the Uruguayan National Agricultural Research Organisation (INIA).

As part of a project funded by INIA, the authors supported the pilot group to deliver the aims during 2018 and 2019. Through workshops and regular meetings, the support focussed specifically on building trust in the modelling and the resulting scenarios. While there are plenty of examples of stakeholder collaboration in IWRM, this work is different in that the stakeholders are actually the hydrological modellers, and the role of "experts" has been mainly in facilitation and capacity building.

Here, we report on both the process and the outcomes. We focussed on credibility, salience and legitimacy in the overall process. As part of this, the group worked through a range of decisions which related to 1) the reliability and accuracy of the input data; and 2) how the real-world processes in the catchment were simplified into model processes. Over the period of the project, the group transitioned from dependent on the "experts" in the beginning, to independent modellers and decision makers halfway through 2019.

Keywords: *Integrated Water Resource Management, hydrological modelling, stakeholder modelling*

The role of simplified scenario assessment in planning for sustainable land-use and food systems

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Abstract: Contemporary food and land-use (FOLU) systems are highly vulnerable to environmental, economic and institutional pressures that limit the capacity to fulfill sustainably societal needs. As change forces intensify, globally coordinated actions to increase the resilience and effectiveness of FOLU systems are required. The Food, Agriculture, Biodiversity, Land Use, and Energy (FABLE) consortium (www.foodandlandusecoalition.org) is an international knowledge network involving around eighteen country teams. The consortium evaluates the technical feasibility of global land-use sustainability targets and potential impacts on international markets for food and non-food commodities from the FOLU system. This globally coordinated exercise is the first of its kind.

The preliminary results from FABLE's first report suggest that there are pathways to more sustainable and resilient FOLU systems better tuned to achieving sustainability and climate targets both at the national and global levels. However, this requires the implementation of an integrated framework to organize strategies from a local to a global perspective and define and pursue long-term strategies driven by relevant stakeholders. An optimistic pathway at the high end of technical feasibility (and dependent on several crucial assumptions) could enable significant greenhouse gas emissions (GHG) reductions in the Australian FOLU system and increase the amount of land that supports biodiversity by 2050. This exercise provides insights into the conditions needed for national FOLU systems to reach specific sustainability targets. It also contributes to assess how country-specific pathways align relative to the achievement of global goals around food security, forest cover change, biodiversity, and GHG emissions from agriculture and land use change.

Enabling this collaborative analysis is the FABLE calculator (a flexible, reduced-form representation of domestic land and food systems developed in Microsoft Excel). Each country in the FABLE consortium has adapted this tool to their context using country-specific data and knowledge base (e.g. studies of dietary shifts, system responses to technological change). For example, in the Australian version of the calculator the default parameterization of crop and livestock productivity, and parameters related to biomass growth impacting carbon sequestration were modified to better represent Australian conditions. The calibration of the calculator and the definition of a potential pathway to achieving FABLE targets were informed by results of integrated assessment models of the Australian FOLU system (e.g. the Australian National Outlook 2019 and the Deep Decarbonization Pathways project) and by experts' opinions.

Although spatially explicit, sector-level modelling offers significant advantages over the FABLE calculator (e.g. commodity production informed by market prices), the extensive calibration and flexibility of the calculator allow quick exploration of potential trade-offs and benefits of interventions in the FOLU systems. Open-source tools can be linked to the calculator allowing global parameter sensitivity assessments and to account for the impacts of uncertainty in assumptions, parameters, and input data. This modelling flexibility is important when it comes to supporting long-term thinking and target-focused strategies to solve problems that require the coordination of national efforts. The calculator could be an asset for countries that lack the capability to develop, maintain, and run more complex models (e.g. partial equilibrium sector models). Simplified tools for FOLU systems scenario assessments, when backed up by reliable data, may have a role to play even in developed nations by offering a compelling interface over which scientists and stakeholders could interact and discuss changes in pathway assumptions and observe the corresponding effects across multiple indicators almost in real time.

Keywords: *SDGs, agriculture, land-use, decision-support, drivers*

An integrated framework for exploring the feasibility of managed aquifer recharge

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Abstract: Under climate change, water is becoming scarcer, increasing the need to share it between the environment, human consumption and industry (including agriculture). In Australia, historic over-extraction of water for agriculture has degraded the environment. The government has intervened, in part by reducing water entitlements. In response, irrigators have adapted their production systems to increase water efficiency. With climate change, irrigators will need to continue to adapt.

Managed Aquifer Recharge (MAR) is the purposeful recharge of surface water into aquifers, for extraction at another time. MAR offers an option to store surface water underground, avoiding evaporative loss, and evening out stochastic surface supplies (particularly if floods and drought are more common under climate change). However, the feasibility of a MAR scheme is site dependent, and needs to be evaluated across all criteria, including its technical feasibility, financial viability, ecological risk and social acceptability, all within existing or adjusted legislative boundaries (see Box 1).

Box 1: Criteria to evaluate MAR feasibility

1. Is there **demand** for more water or greater water security?
2. Is **water available** to be banked underground?
3. Is it **technically feasible**? (e.g. aquifer storage available to store water)
4. Is it **financially viable**?
5. Potential for **ecological cost/benefit**?
6. Is it **socially acceptable** amongst key stakeholders (irrigators, stakeholders and wider community)?
7. What **legislative and policy** changes could/would need to be changed to allow it?

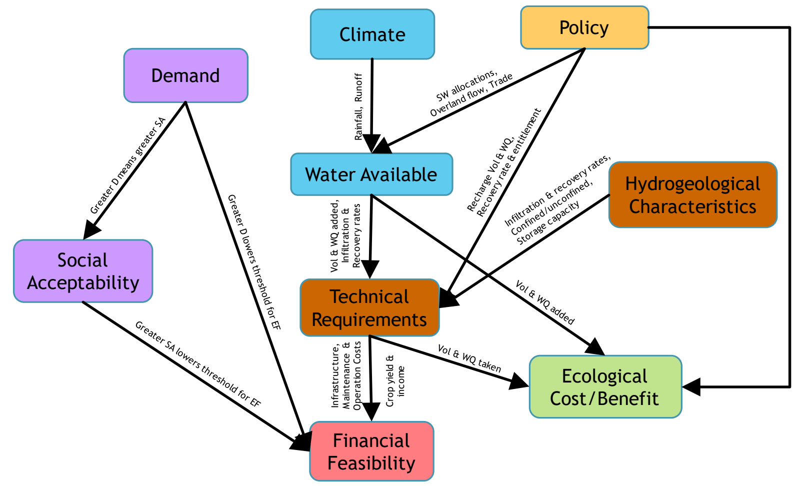

Figure 1. Initial conceptual diagram of MAR feasibility

An integrated framework is being developed to provide guidance as to when and where MAR might be a feasible option for irrigators. The initial conceptual diagram of the framework is given in Figure 1. It will be further developed in consultation with stakeholders from the Murrumbidgee region (NSW) (including irrigators, policy and industry representatives, and water and environmental managers), and researchers (from hydrological, governance, economic, and social disciplines), through a series of workshops, meetings and interviews. The process allows locals to contribute to the evaluation of a new opportunity for water management and give them ownership to the outcomes. The collaboration is also intended to facilitate discussion beyond existing policy boundaries to a new set of rules that's acceptable to all stakeholders. The framework will inform the later development of a modelling tool that uses the Bayesian network approach to integrate information from different sources, and quantitatively explore MAR options under uncertainty with stakeholders.

Keywords: *Irrigated cotton, water policy, Bayesian networks, managed aquifer recharge*

Synthesising multiple observations into annual environmental condition reports: the OzWALD system and Australia's Environment Explorer

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Abstract: Routine, nation-wide environmental data collection, analysis, and reporting remains a challenge in Australia. We wished to test what environmental data is already being collected and can be usefully synthesised, interpreted and reported upon, and to develop a deeper understanding of the scientific and technological opportunities and challenges. To that end, we developed a fully functional annual environmental reporting process, incorporating an automated workflow for data acquisition, integration and summary; a website to deliver the summary the data in a visually informative form; and an annual interpretation, reporting and communication process. Here we report mainly on the technological aspects.

The Australian Water and Landscape Dynamics (OzWALD) system is a data production workflow that can be run on demand. It includes the following components: (1) *Data acquisition* from several gridded climate and satellite data sources; (2) *Data reformatting*, e.g., spatial sub-setting, reprojection, temporal aggregation, and vector-grid transformation; (3) *Data fusion and enhancement*, referring to the blending of like data into a single best-estimate data set, and the improvement of desirable data characteristics, respectively. This results in a blended satellite-gauge precipitation data set, an internally-consistent set of dynamic water and land surface properties derived from satellite products (WALDMORF), and downscaled climate data at 500-m resolution; (4) *Model-data assimilation*, where a biophysical model of the same lineage as the AWRA Community Modelling System is infused with the observational data to estimate additional variables (soil moisture, streamflow generation and vegetation carbon uptake); and (5) *Statistical summary* by year, region and land use type, deriving temporal and regional statistics, used predominantly for web-based visualisation.

A website, *Australia's Environment Explorer* (AEE, www.ausenv.online), was developed to allow users visualise and explore environmental changes by region, location or land use type. The data can be queried in different ways and are visualized in charts. There have been four annual updates to the AEE since 2016, coinciding with the accompanying *Australia's Environment* report and public briefing. In addition to the AEE, the report also synthesises information from other sources and interprets specific events and temporal trends in global or non-spatial data.

Our experiences demonstrate that it is feasible to produce useful, observation-based annual environmental reports. Developing the experimental system and reporting process produced valuable insights, including: (1) the unstable ad continually evolving spatial environmental data services environment is a challenge for maintaining an operational workflow; (2) the rapid development of open source and cloud technologies provides major opportunities and efficiencies; (3) regular, detailed and accurate land cover and land use mapping will be required to achieve successful environmental accounting; (4) the abundance of past, current and future satellite mission observations provides many opportunities for environmental reporting; and (5) obtaining regular and reliable data on biodiversity remains a major challenge. Our goal is to continue, and as much as possible, improve the annual modelling and reporting process until a similar service is available from another source.

Keywords: *Data fusion, model-data assimilation, environmental data, spatial web services*

Bilevel optimisation as a solution method for an agri-environmental principal-agent problem

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Abstract: Recent computational advances in environmental modelling have enabled modellers to predict the impacts of spatially distributed management practices on environmental quality throughout agricultural, forested, urban, and mixed-use watersheds. In addition, real and hypothetical incentive policies – as well as the interactions between policymakers and policy followers – have been simulated using agent-based modelling techniques as well as optimisation and multi-criteria decision-making methods.

In this paper, we use bilevel optimisation as a solution method for solving an agri-environmental principal-agent problem—that is, to create spatially targeted environmental incentive policies to improve water quality. In constructing the problem and solution framework, we draw parallels between agent-based and bilevel approaches as means to simultaneously consider both the objectives of the policymakers and policy followers. Our case study investigates the Tully catchment, which is dominated by sugar cane farming and a major contributor of nutrient runoff from northeastern Australia to the Great Barrier Reef Lagoon. We compare uniform and spatially targeted policies that offer payments for agricultural producers to implement discrete reductions in fertilizer application rates, and the resulting policy solutions highlight the optimal trade-offs between policy cost and nutrient reductions. In addition, we show that targeting policy incentives based on soil type achieves greater efficiencies (i.e., less policy cost, and less nutrient runoff) than simply offering different incentives for each fertilizer reduction. By leveraging knowledge of the spatial distribution of soil type throughout the catchment, our results suggest that policymakers can construct more efficient policies that will ensure adoption and achieve considerable nutrient load reductions at feasible costs. This framework for optimizing incentive policies could be extended to include more complicated and realistic policy options, and it could also be applied in other watersheds dominated by agricultural, forested, urban, and mixed land uses.

***Keywords**: Environmental modelling, agent-based models, bilevel optimisation*

Towards a multi-scale optimization model to support integrated river basin management: the case of the Cantabrian region, Spain

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Abstract: Uncontrolled water resource allocation for irrigation or drinking water provision can alter flow magnitude variability and lead to impairments of aquatic ecosystems. Integrated river basin management plans (IBM) thus need to deal with multi-objective problems, encompassing water requirements for ecosystems (such as environmental flows) as well as human water needs. However, since land use affects water regime variability, the identification of best management actions at the basin scale can be very complex. Hence, we suggest a methodology that considers both anthropogenic and environmental objectives at multiple scales as a base for a water resource allocation framework.

Figure 1 presents the conceptual methodological framework that also includes the identification of targeted water management actions at the reach scale. The proposed methodology considers the IBM objectives for the basin (e.g. ecological status, drinking water provision) and alternative land-use scenarios that could modify water regime variability (i.e. total forest cover). Therefore the optimization model evaluates a series of ecological indicators (e.g. recruitment, spawning) of the river eco-system representing phenological stages of fish species, macroinvertebrate groups, and macrophytes. These indicators have been selected as they capture relevant ecological processes and define the ecological status of the river system. Hydrological dependence from ecological indicators will be expressed through a set of environmental flow parameters (e.g. flow magnitude, freshes timing, and duration). An indicator relationship's network is defined through conditional probability tables by following a cause-effect rationale. The use of conditional probability allows the consideration of nonlinear effects propagation throughout the network as a consequence of a series of antecedent conditions. The probability of a certain water reliability level will be maximized by applying a genetic algorithm. The algorithm will first search for hydrological conditions (i.e. probability distributions in environmental flow's nodes) that will maximize the ecological nodes based on a series of constraints (i.e. species preferences for hydrological conditions). Then simulation outputs will be optimized in order to provide the quantity of water that can be abstracted without impairing the ecosystem, considering a series of supply constraints. Land-use scenarios (i.e. forest cover) will be evaluated in order to assess how alternative land cover management strategies can affect hydrological variability and hence water availability for consumption.

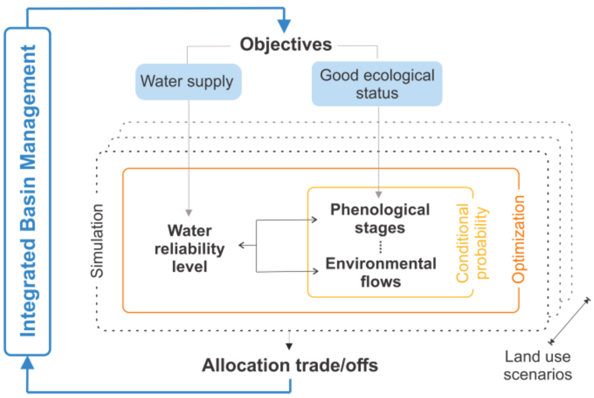

Figure 1. Illustration of model framework for the optimization of basin management objectives

We expect that the simulation will provide land and water management options to reduce trade-offs among different uses of water and ecosystem conditions across basins. As an example of model structure and functioning, the case of a water-stressed basin in the Cantabrian region (Northern Spain) will be presented.

Keywords: *Multi-objective optimization, environmental flows, conditional probability, integrated basin management*

Towards multifunctional agricultural landscapes: Assessing and governing synergies between food production, biodiversity and ecosystem services

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Abstract: The increasing demand for agricultural products calls for an improved understanding of synergies between biodiversity, food and energy production and ecosystem services as well as for the development of policy measures to support these synergies. The BiodivERsA funded project TALE contributes to such an improved understanding by identifying and quantifying the trade-offs and synergies between food production, biodiversity and selected ecosystem services, developing scenarios on how future land use can look like under different policy priorities (land sharing, land sparing and business-as-usual), identifying optimal land use strategies and analyzing existing policy measures to assess their effectiveness to support such strategies.

The studies were carried out in a set of representative agricultural landscapes in Germany, Switzerland, Austria, The Netherlands and Spain. The methodological steps of the project consist of i) designing and implementing a systematic stakeholder integration process (incorporation of expert knowledge) in all project phases to ensure practical relevance, ii) developing a set of land use scenarios and land use policies and iii) developing a framework that links biophysical (SWAT for agricultural yield, streamflow and water quality) and statistical models (random forest models for breeding habitats for birds) with optimization algorithms. Moreover, TALE provides an innovative online learning environment that is accessible both for experts, students and the general public.

Stakeholder guidelines were developed to initiate a bottom-up process for ensuring co-design of knowledge within the project. By using the stakeholder-defined scenarios as model input, we received information on their impact on selected ecosystem services and biodiversity. In addition, explorative modelling was carried out to explore limits but also further potential of providing several ecosystem services of a region.

The scenario results for the German case study indicate strong trade-offs between agricultural production and both bird habitat and water quality. In order to minimize these trade-offs, we applied a genetic algorithm to explore the Pareto-optimal spatial targeting of scenario options at the level of Hydrological Response Units. We found that all scenarios can be dominated in multiple objectives at the same time. To eventually identify preferable land use configurations, we applied a multi-criteria decision analysis based on interviews with stakeholders with different backgrounds (e.g. water experts, nature conservationists, farmers, etc.). We used here a combination of qualitative interviews, parallel coordinates plots and AHP that shows a promising way how multi-objective optimization results can be communicated and used for an information-based decision-making process.

Keywords: *Integrated modelling, integrated assessment frameworks, multi-objective optimization, stakeholder preferences, communication*

Integrated assessment frameworks for understanding pathways for socially inclusive agricultural intensification

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Abstract: Alleviating poverty through agricultural development is a challenge that requires sound understanding of the social, market, environmental and institutional settings. An integrated assessment (IA) process can help to clarify and examine the nature of the interactions between these diverse processes and facilitate concerted and collaborative efforts from interdisciplinary teams. This paper provides an overview of IA frameworks developed for a project aimed at identifying opportunities and policy options that promote more socially inclusive and sustainable agricultural intensification in rural communities in West Bengal and Bangladesh.

The IA frameworks were intended to provide a 'big picture' of the social and agricultural systems we are researching, and to improve understanding of the interrelationships between the diverse processes, and the pathways between drivers and outcomes. This paper describes the methodological process followed in developing these frameworks (Figure 1). The frameworks are grounded in both theory and observations from project activities, and were iteratively developed with input from stakeholders and domain experts. The frameworks then formed the basis for further (semi)quantitative or qualitative analysis, demonstrated in the study through the development of semi-quantitative models (fuzzy cognitive maps) and narratives.

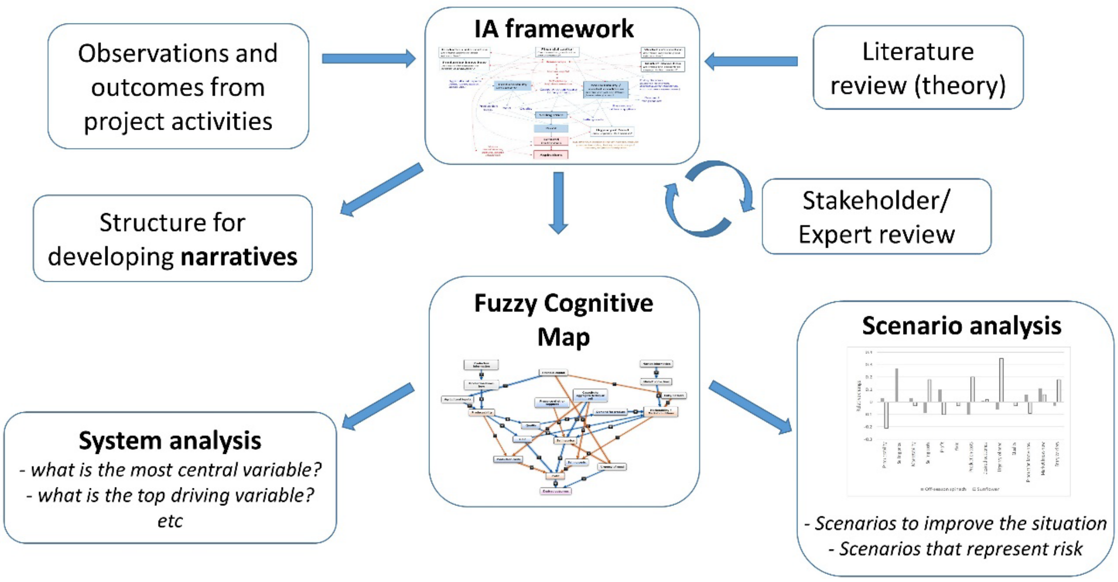

Figure 1. An overview of the integrated assessment process

As a modelling process, an outcome of the IA work has been the formalisation of our common understanding of the system. The IA framework development also facilitated an explicit integration process, as it involved all team members who were required to consider the linkages between their usual fields of study to the wider system, thereby promoting interdisciplinary thinking. The IA frameworks have also become a discussion and learning tool to test implications of system interventions or perturbations.

Keywords: *Integrated assessment, interdisciplinary research, modelling process*

Unified natural hazard risk mitigation exploratory decision support system (UNHaRMED): Pathways for development and utilisation

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Abstract: The Unified Natural Hazard Risk Mitigation Exploratory Decision support system (UNHaRMED) is underpinned by two driving principles: (i) prevention is better than cure and (ii) tomorrow's risk is a function of decisions made today. It can be used to explore how the spatial variation of risk due to a number of natural hazards is likely to evolve on an annual basis in response to a combination of (i) external drivers that are generally beyond the control of local decision-makers (e.g. climate change, population growth) and (ii) a range of mitigation strategies (e.g. land use planning, land management, structural measures, changes in building codes, community education). Changes in hazard, exposure and vulnerability are modelled explicitly, as well as potential interactions between them. The hazards currently included in the UNHaRMED software framework are bushfire (wildfire), earthquake, coastal inundation and riverine flooding, although the incorporation of heatwave is being explored. The dynamics of changes in exposure are modelled using coupled land-use and building stock models. The vulnerabilities of different types of buildings to the various hazards are represented by damage curves and social vulnerability is represented by the number of people affected, as well as demographic profiles.

In order to maximize the chances of the adoption of UNHaRMED in practice, the conceptual modelling framework, underpinning models and decision support software were co-developed with over 40 government agencies in four Australian states, namely South Australia, Victoria, Tasmania and Western Australia. This involved coupled development and use processes, each of which involved interactions between potential end users, technical experts (e.g. scientists, engineers, modellers) and software developers. The formal link between development and use is considered particularly important to provide an opportunity for end users to interact with the decision support system (DSS) and provide feedback to enable the system to be refined to meet end user requirements and expectations.

With five and a half years of the research project completed, and another one and a half years to run, the adoption of the UNHaRMED applications in the four states are at different stages, due to a combination of differences in the timing of their development, end user capacities and policy environments. However, based on our experience across all states, the following factors play a major role in the successful adoption of integrated DSSs in practice: (i) the involvement of end users at all stages of system development via participatory processes, including the setting of the policy context, how the system will be used, what outputs / indicators are required etc., (ii) maximization of the use of data, information and component models that the end users are familiar with and trust (iii) a favorable policy environment, resulting in a realization of the need for and an openness to embrace the system, (iv) the opportunity to work with end users to apply the system to case studies of interest, enabling the value of the system to be demonstrated and end users to become familiar with the system, (v) a consistent group of end users that is involved throughout the development and use processes, (vi) one or more "champions" who promote the system within their own and other organizations and (vii) the presence of a "critical mass" of end users.

Keywords: *Decision support system, disaster risk reduction, bushfire/wildfire, flooding, coastal inundation*

From data to decisions: Bayesian inference for differential equation models of food web networks and seagrass ecosystem trajectory

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Abstract: Data-driven modelling is proposed as a means to produce forecasts that can inform decision-making. This goal is already realised in the field of weather science. However, in ecology, this goal has been hampered by the variability inherent in ecological processes and a fear of providing forecasts that are inaccurate or, in the worst case scenario, misleading and potentially detrimental to the environment. These fears must be overcome: Forecasting ecosystem responses to environmental and anthropogenic changes is challenging but necessary to better inform environmental decisions.

In this talk we demonstrate how Bayesian inference, combined with ecological data and appropriately chosen mechanistic models, can be used to obtain predictions, including uncertainty, that are useful for informing environmental decisions. We demonstrate this with two case studies: (1) species interaction networks, specifically the potential impact of future perturbations such as individual species eradications or reintroductions, and (2) seagrass ecosystem decline, specifically accounting for the cumulative impact of light and temperature stressors. Bayesian inference in these case studies is used for model-data calibration, and its implementation, which will be briefly summarised in a non-technical manner, is carried out via Sequential Monte Carlo sampling (an ensemble method which is a computationally-intensive but potentially superior approach compared to Markov Chain Monte Carlo sampling), and variational Bayesian inference (an approximation which transforms the model-data calibration, including uncertainty, into an optimisation problem). A nice byproduct of this approach is that it can identify whether the data are sufficient to inform the model; i.e. whether more data are needed and/or a less complex model would be more suitable.

Through these two case study examples, we present a pathway forward for ecological forecasting that rigorously propagates variability in experimental observations through to uncertainty in model predictions. Overall, our findings show that these models do not need to produce well-constrained predictions before they can be used to inform decisions that improve environmental outcomes.

Keywords: *Cumulative stressors, decisions, ecological forecasting, prediction, uncertainty propagation*

Optimising invasive species removal in highly uncertain systems

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Abstract: Ecological systems are notoriously complex, making effective management challenging. While scientists are constantly working to increase our knowledge, it is in some senses a losing battle, because not only are ecosystems complex, they are idiosyncratic, varying across space and always evolving. Hence, to efficiently improve our management strategies, we must first know which aspects of the system are critical for shaping good management strategy. While there is certainly overlap between predicting future dynamics and developing good management, something important for one is not automatically important for the other. A simple example is the costs involved with management. Optimal strategies can't be developed without knowing the costs, but costs themselves are not relevant for forecasting system dynamics.

Mathematical modelling and optimisation is a useful way to understand how ecological complexity and system uncertainty map on to optimal decision-making. Through simulation, we can adjust one aspect of a system at a time, to see how it affects the optimal management strategy, giving us insight into what matters for management. This deeper understanding allows scientists to focus their research efforts on the most critical aspects of a system, providing in turn a bigger impact for scientific research.

In this talk I will discuss how I view uncertainty in ecological models, with a focus on invasive species management. Invasive species are a global problem, causing declines in endangered species and impacting agriculture. Hence, there are significant resources spent on their control and removal. Invasive species arise in many contexts, interact with different species, thrive in different areas and can be difficult to capture, depending on the ecosystem structure. Using optimal control theory, we can derive the optimal management strategy for an invasive species population model, across a wide range of parameters, thus determining they key areas of uncertainty to study further and what type of systems can be managed without further information.

Keywords: *Optimal control theory, dynamic optimisation, decision-making under uncertainty, differential equation models*

Understanding the uncertainty around simulation models: Conceptual and empirical insights from transdisciplinary agricultural research

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Abstract: Decision making in farming operations and the environmental regulation of agricultural systems are increasingly dependent on information derived from data-rich, digital sources. Environmental simulation models can help to interpret the growing amount of data and to manage the complex uncertainties that accompany decision making in these contexts. While simulation models may reduce some of these uncertainties, they cannot address others and might even introduce new uncertainties. Model developers, regulators and other end users make frequent reference to uncertainties, but it is often unclear which specific aspects of a given model are discussed or whether the uncertainties in question are even within the model's intended scope. As a result, discourses concerning uncertainty can promote a plethora of meanings and interpretations. Developers' and users' communication around uncertainty within decision-making processes can therefore remain vague and ineffective unless these diverse meanings are understood by all parties. Drawing on transdisciplinary research in the agricultural/environmental sector, this paper proposes a conceptual framework to facilitate meaningful communication around complex uncertainties and the role of simulation models in environmental decision making (see Fig. 1). We provide corresponding empirical insights from a study using the Agricultural Production Systems sIMmulator (APSIM).

Our conceptual framework builds on recent scholarship that distinguishes between the direct uncertainty associated with a specific simulation model itself, including irreducible uncertainties (e.g. aleatory uncertainty), and indirect uncertainties around the model, which concerns the quality or underlying knowledge or users' trust. We expand this useful distinction by adding a third layer of uncertainties that emerge from the wider social, political and economic context within which models are embedded. Additionally, we draw attention to the processes of data generation and model building themselves, which are, in turn, influenced by contextual factors (e.g. political priorities). This paper details crucial implications from this framework.

We demonstrate how these implications manifest empirically by presenting findings from social research around APSIM when simulating production scenarios under different irrigation patterns. Following these insights, we propose that framing uncertainty in this way is useful for several reasons.

First, it helps to identify the different types of uncertainties involved in the building, communication and use of simulation models. This, secondly, allows transdisciplinary research teams to delineate their work areas and establish productive collaboration in order to recognise leverage points for uncertainty reduction. Third, the framework facilitates meaningful developer-user dialogue around models' strengths and limitations in addressing complex uncertainties, which is a crucial part of expectation management and model improvement. Fourth, this understanding can form the foundation for a more comprehensive decision-making framework for contexts where a lot of information and uncertainty emerge from data-rich, digital sources.

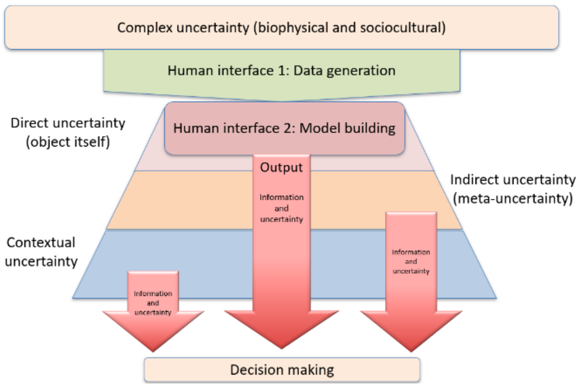

Figure 1. Conceptual framework for understanding complex uncertainties and the role of simulation models.

Keywords: *Uncertainty framework, decision making, complex uncertainties*

Climate informed robust decision analysis for environmental flow risks in the Lower Murray-Darling Basin, Australia

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Abstract: Long term planning for hydrological systems has traditionally accounted for future climate risk using a top-down approach, where climate change projections from global and regional climate models are used to drive hydrological models to assess climate change impacts to inform adaptation options. The projections of water futures span a large range due to the cascading uncertainties associated with the knowledge and modelling of global and regional climate, internal climate variability, climate downscaling for hydrological impact modelling, and the extrapolation of hydrological models under some projections of climate change. The performance of hydrological systems (e.g. ecological, water storage, hydropower) also typically display non-monotonic responses to streamflow further contributing to the uncertainty associated with using climate projections to inform risks to these systems. The large uncertainty in plausible futures presents a significant challenge to planning and adapting hydrological systems to reduce climate change risk.

The use of robust-assessment approaches, often referred to as a bottom-up approach, which focus on the system vulnerability space, provides an alternative to the traditional top-down climate impact assessments. The focus on system vulnerabilities allows for a range of exogenous drivers, including climate, to be considered. We use a robust-assessment approach known as decision scaling[1,2,3] to assess climate risks to several key environmental assets in the Lower Murray-Darling Basin in south-east Australia. Central to the decision scaling approach to assessing climate risk is an assessment of the system's sensitivity to climate, or a climate stress test, where climate statistics are modified in a weather generator, capable of replicating daily through to interdecadal characteristics, to sufficiently stress the system and in this case yield unacceptable ecological outcomes. The climate stress test identifies the climate parameters or characteristics to which the system is most sensitive and provides context for new climate information, be this information from extended gauged records, paleoclimate data, or climate and hydrological models as they arise without the need for further detailed system model runs. Adaptation options through new infrastructure, enhanced water management, and changed practice and policies can also be directly assessed.

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Acknowledgements

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Keywords: *Climate sensitivity analysis, decision scaling, bottom-up approach, environmental flows, hydrological system, Murray-Darling Basin*

Emulation-based sensitivity analysis for distributed water quality models

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Abstract: Distributed water quality models present several challenges at the same time. Firstly, available water quality observations tend to be scant in both space and time and also contain large errors. This accentuates the need for sensitivity and/or uncertainty analysis of model predictions, typically undertaken via sampling of model parameter space and running the model forward for each sample. These models also contain large numbers of parameters, making adequate coverage of the parameter space by sampling a challenge. Some models may also have long runtimes accentuating the need for efficient sampling of the parameter space. A common technique to reduce the number of samples and associated model runs is to identify and fix those parameters that are deemed insensitive at a constant single value. However, more complete SA analysis must be undertaken in a framework aimed at minimizing the appropriate error caused by fixing identified insensitive parameters, especially when little prior information is available, which is often the case for distributed water quality models.

We are using a methodology to deal with these problems (large numbers of parameters and long runtimes). We illustrate this using a Dynamic SedNet Model (DSM) for a catchment draining towards the Great Barrier Reef in Australia. A surrogate modelling approach is used to address the long runtime problem. The surrogate model emulates the original model and reproduces its response surface of outputs effectively in a computationally efficient manner. The Polynomial Chaos Expansion (PCE) method is chosen because of its computational efficiency and accuracy in approximating the response surface and its ability to provide Sobol' sensitivity indices for free.

We built PCE models for different quantities of interest, here as percentiles of pollutant load. SA was then conducted using the PCE surrogate model. Results show that PCE is an efficient method in undertaking SA for DSM models. We also propose a step-wise, systematic process for establishing the errors in fixing parameters, illustrating this for our DSM catchment model. It assumes the emulator obtained by not fixing any parameters as the truth or benchmark against which it calculates the error for different parameter fixing options. It starts with the step of fixing the most insensitive parameter, calculating its departure from the truth, and then adds in the next least sensitive parameter to derive that departure and so on. The step-wise process uses the sensitivity indices obtained for free from the emulation. The process is cheap computationally, the main expense being the building of the emulator.

Keywords: *Distributed water quality models, sensitivity analysis, emulation*

Evaluation of Mathematics teaching strategies in Australian High Schools

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Abstract: Achievement in mathematics can act as an indicator of student ability in subjects that require mathematics proficiency such as science, technology and engineering. Analysis of data from the Programme for International Student Assessment 2012 study on high school students from Australia was performed to evaluate the potential effects of various teaching strategies on mathematics outcomes. Aspects of teaching considered included student-teacher relations, classroom management, teacher support, disciplinary climate, cognitive activation, formative assessment, student orientation, and teacher directed instruction. Parent education levels and economic status were also considered as potential influences of performance and were found to have significant effects on mathematics performance with students whose parents were more highly educated recording higher results, on average. Cognitive activation, disciplinary climate, student-teacher relations, and vignette classroom management were found to have a significant positive impact on mathematics performance. Student orientation had a significant negative effect on mathematics performance and greater use of it was associated with lower mathematics achievement. The results of this study can offer valuable insights into how teaching strategies, along with other factors, can be augmented to help improve confidence in, and hence, performance in mathematics.

Keywords: *Multilevel modelling, teaching strategies, mathematics*

From conjecture to application: developing tangible steps to integrate gender into water management modelling

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Abstract: Access to and control of water use is framed by gender dynamics. Men and women have differing relationships with water in terms of their needs, priorities and responsibilities relating to its use. Water management outcomes can have unacknowledged gendered effects which entrench social disadvantage. Where water management decisions are informed by modelling, it is important to acknowledge these gendered differences in the initial model design. Socially inclusive modelling design is fundamental to the establishment of equitable water management planning, and more broadly, to improved gender and development outcomes for communities. Although acknowledged to be important, the need for social inclusion is rarely acted upon in modelling work, perhaps because there is little guidance available. The challenge is in knowing how to operationalise gender considerations into water modelling design.

Packett et al. (2018) give some preliminary guidance on how to mainstream gender considerations into water management model design, use and interpretation. They outline three phases of model development and use: problem framing and conceptualisation; model construction, documentation and evaluation; and model interpretation for supporting decisions. For each of these phases, examples are given of how gender considerations could be applied, and their impact on model development decisions and outcomes. The report and examples are based on a literature review, and the recommendations from the report have not yet been applied to a modelling project. In order to move from conjecture to application, modellers need clarity on tangible steps that can be taken.

The goal of our work is to develop and test awareness-raising material which bridges this gap. These modules act as conversation starters for modellers to explore how including gender considerations could impact modelling practices and outcomes. Awareness-raising material has been developed in accordance with Kolb's learning cycle (Kolb, 2014), providing thought-provoking exercises which span different model development phases. The first module exercise is to help participants acknowledge that models are sensitive to the influence of subjective modelling choices, and to reflect on their own assumptions which affect model choices. Participants are given reading recommendations directing them to relevant literature in order to gain a more detailed understanding on this point. Other modules explore further applications to model construction and interpretation. In developing these modules with colleagues, and gathering their feedback, we have found that this material provokes useful reflections on underlying personal assumptions, modelling practices, choice of reporting indicators and their documentation. Our presentation will be based on these reflections.

Stakeholder engagement is crucial to this work and reveals a potential for this approach to be a useful entry point for broader social inclusion in modelling and analysis. Many of the steps required for integrating gender could also be applied when addressing other social inclusion objectives. We see good opportunities for deeper reflections on the role of modelling in supporting equitable outcomes. The approaches we are exploring require further rigorous testing and evaluation against appropriate criteria. We aim to build up a set of evidence-based examples to support our work and substantiate the importance of integrating considerations of social inclusion into modelling practices. We would like to invite the audience to share their examples and suggestions which are relevant to this work.

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[1] These authors contributed equally to this work

Keywords: *Gender, social inclusion, integrated water resource modelling, awareness-raising*

Exploring the effects of linguistic and cultural similarities between interviewer and respondents' behavior in large scale surveys

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Abstract: In this paper, we explore the factors affecting respondents' degree of cooperation in large scale household surveys, with a focus on a multi-linguistic society. A detailed examination of the issue is conducted by using the Pakistan social and living standards measurement (PSLM) survey, 2014-15 data, gathered through a nationwide sample of 78,635 households. We observe that respondents' attention is not only affected by their socio-economic conditions, but also the linguistic similarities between interviewer and interviewee, which play a significant role in this matter. We considered *respondent behavior* (RB), assessed by enumerator and quantified on a Likert scale with six categories such as, "Co-operative = 1, Normal = 2, Reluctant = 3, Non-serious = 4, Refusal = 5 and Non-contact = 6" codes, as the study variable. The initial exploratory analysis revealed that at a national level, 29.57% of the respondents were co-operative and 62.19% were categorized with a normal attitude by interviewers. Further, 6.18% of the total 78,635 respondents were assessed as reluctant and the remaining 2.04% respondents were reported with non-serious behavior. Based on literature and experts' opinion, a range of explanatory variables are also taken into account in this study. Inspired by the American Statistical Association recommendations, we took *language of the interview* (L) as one of the explanatory variables. The PSLM 2014-15 questionnaire recognized nine languages including "Urdu = 1, Punjabi = 2, Sindhi = 3, Pushto = 4, Balochi = 5, Kashmiri = 6, Balti = 7, Hindko = 8, Siraiki = 9", whereas code 10 was assigned to other minor languages. We observed that most of the interviews were conducted in *Punjabi* (almost 26% of total sample). The five languages, *Urdu*, *Punjabi*, *Sindhi*, *Pushto* and *Siraiki* cumulatively contributed almost 97.1% and the contribution of *Urdu* (national language) remained almost 23%. Next, we used *household education level* (Edu) as a potential explanatory variable. The cumulative contribution of categories between class 1 to class 5 (inclusive) in terms of percentage, in defining educational level of a household remained almost 67.7%. Whereas, class 6 to class 10 (inclusive) contributed almost 15.4%. *Household health status* (Sick) is considered as a possible determinant of respondents' attitude. Exploratory analysis of the PSLM data revealed that almost 71% of the sampled households reported that no one in household was sick or injured during the last two weeks, whereas 22.5% of households documented one sick or injured member. Given the importance of economic factors as an important deriver of social conduct, we also considered *household economic progression* (Eco) as an explanatory factor in this study. The PSLM (2014-15) survey questionnaire allowed for the assessment of relative progression of economic conditions of households with respect to the previous year. Based on the data, we observed that the most frequently reported response remains "Like before", where almost 48% of the respondents of the survey remained. Cumulatively, almost 19% of the respondents felt that they are better off as compared to the previous year, whereas, almost 36% (cumulatively) of households suffered a worse economic situation than last year. Only 0.17% of the survey respondents chose the option of "Do not know". Lastly, the locality of the interviewer (rural or urban) was considered as a determinant of respondents' attitude towards survey exercise. We found that, on average rural participants are more likely to have a cooperative attitude when compared to their urban fellows. At the modeling stage, the usual logistic regression, ignoring varying cultural streams of the country, led to un-interpretable and un-cohesive estimates of the factors potentially impacting respondents' response. Based on these observations and to meet the complexity of the socio-cultural diversity of the country, we propose a multi-level generalized linear modeling strategy to investigate the explanatory power of literature based factors which may impact the respondents' behavior in large scale survey exercises.

Keywords: *Household survey data, Multi-level modeling, respondents' behavior*

Inclusive Water Resources Modelling: giving a voice to the 'voiceless'

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Abstract: Integrated Water Resources Management (IWRM) is an approach to watershed management that has gained acceptance, and adoption, by water resource managers, planners and policy makers worldwide. There are many theories as to why this is so – with probably the most likely being that it was the 'right' idea at the 'right' time (ref e.g. Allouche 2016). The 1992 Dublin Statement on Water and Sustainable Development brought together four principles – that fresh water is a finite resource; that its development and management should be based on a participatory approach; that women play a central role in the provision and management of water; and that water is an economic good. Allouche (2016) argues that the inclusion of the 3rd principle was a sop to the social activists at the time. If this were the case, it was timely and reflected the frustration of those who were marginalised at the time. But how to realise that 3rd principle? Worldwide efforts have resulted in more women and other groups traditionally excluded from water resources planning being involved in IWRM. But at what cost? Particularly in developing countries, women carry a disproportionately heavy load in terms of sustaining families and communities – why expect them to want to attend meetings, and be involved in stakeholder processes that are alien, confronting, and time-consuming? Can we look to the history of how the environment has been mainstreamed in IWRM for guidance? Forty years ago water resource modelling was focussed on maximising water availability to industry (irrigation, hydropower, etc) while minimising risks such as flooding and damage to property. The environment was a 'nuisance' that set constraints on modelling solutions. How things have changed. IWRM demands that the environment be treated as a first-class water user. While it may not be the 'loudest voice' at the table, it is definitely at the table, legitimised through advocacy and the building of a defensible, robust and repeatable ecological response evidence base. Can we do the same for the disadvantaged and marginalised, who are equally 'voiceless', i.e. can we be their voice? Can we build the knowledge base? This is our challenge, and our responsibility, as IWRM modellers – by definition, be it integrated water resources management, or inclusive water resources modelling, we are obliged to incorporate the interests of those who are 'voiceless'. Let us not perpetuate inequality through ignorance.

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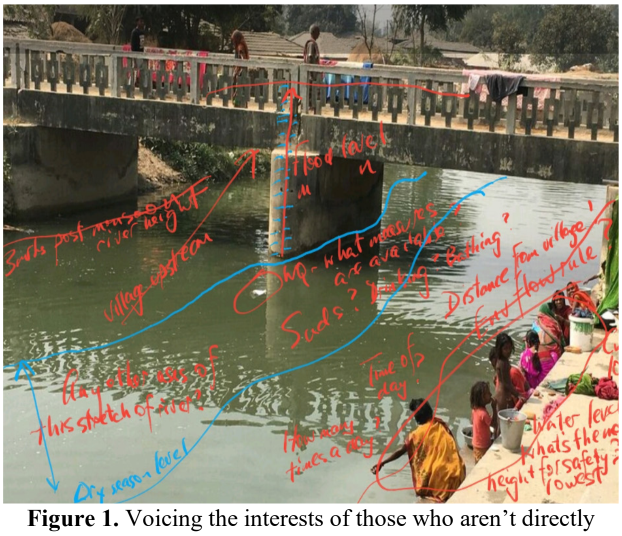

Figure 1. Voicing the interests of those who aren't directly involved in IWRM – conceptualising the river system from an inclusive water resources modelling perspective

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Keywords: *Gender equality, social inclusion, GESI, integrated water resources management*

Reflecting on integrated assessment in the Socially Inclusive Agricultural Intensification (SIAGI) project

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Abstract: Agricultural aide interventions are often intended to help small and marginal farmer households increase their agricultural production, and by doing so, better meet their household needs and improve their social and economic standing. However, intensifying their agricultural production requires them to have the capital assets (financial, human, natural, physical and social) and agency to access and use more agricultural inputs, develop and manage the necessary farm or community level infrastructure (e.g. for irrigation, or post-harvesting), and make informed crop and land management choices. Many small and marginalised farmers are lacking in both capital and agency, which constrains their capacity to engage in, and benefit from, agricultural intensification. In this paper, we reflect on our integration research in the *'Promoting Socially Inclusive and sustainable Agricultural Intensification in West Bengal and Bangladesh'* (SIAGI) project, focusing on the learnings and outcomes of being socially inclusive in our modelling practices. The Ethical Community Engagement (ECE) ethos and practice to which the SIAGI project team has committed has shaped the content of the integrated assessment frameworks that we have developed as well as the process (Figure 1) we used to develop them. Social inclusion is both a core value of the SIAGI project and an outcome against which the impact of the project will be measured.

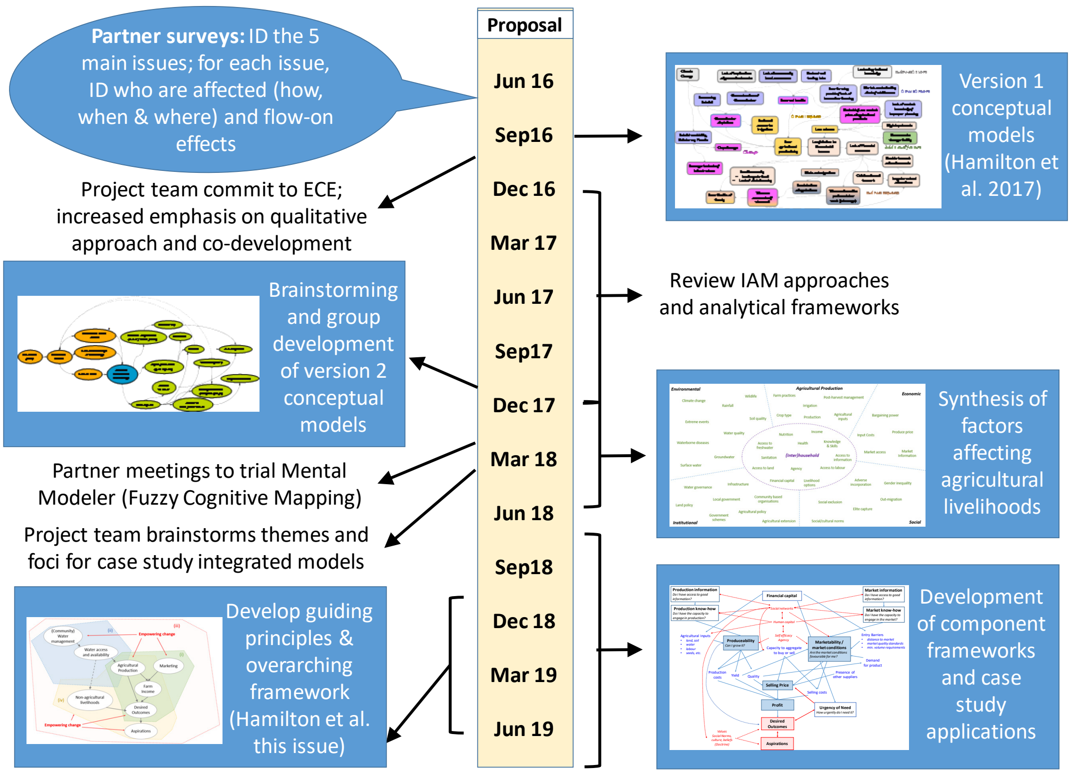

Figure 1. Timeline of key IA activities and outputs in the SIAGI project over the first three (of four) years. Timeline graphics are included for pictorial purposes only.

Keywords: *Social inclusion, transdisciplinary research, research for development (R4D), Integrated assessment (IA) frameworks, ethical community engagement (ECE)*

Communities of practice in building river system models for coastal regions of NSW using eWater Source

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Abstract: River basin water resource planning models are a core building block to provide input to statutory water planning processes in NSW. The Water Modelling Team of NSW Department of Planning, Industry and Environment (DPIE) has been building a new river system models using eWater Source software (replacing existing IQQM models where available) in the inland and coastal regions. One of the key objectives of new model development is to build high quality, robust and fit for purpose models, which suitable for running a wide range of scenarios to meet a range of accountabilities under NSW and Commonwealth legislations. A systematic, consistent and transparent approach (Figure 1) has been used by DPIE in the model building process across using communities of practice including agile project management, modelling guidelines developed in-house over 20 years and industry best practice developed in collaboration with other jurisdictions.

A series of workflows has been developed and implemented to enhance the efficiency, transparency, provenance and quality assurance in model development and documentation. Internal and external stakeholders have been engaged in different stages of model developments such that the models meet the needs and have the confidence of various stakeholders.

This paper describes the communities of practice used in building new generation models for several regulated and unregulated river basins in Far North and North Coasts of NSW. It explains how the feedbacks from the peer-review and stakeholder engagement processes were captured in the model build with a number of examples of critical success factors and barriers to overcome.

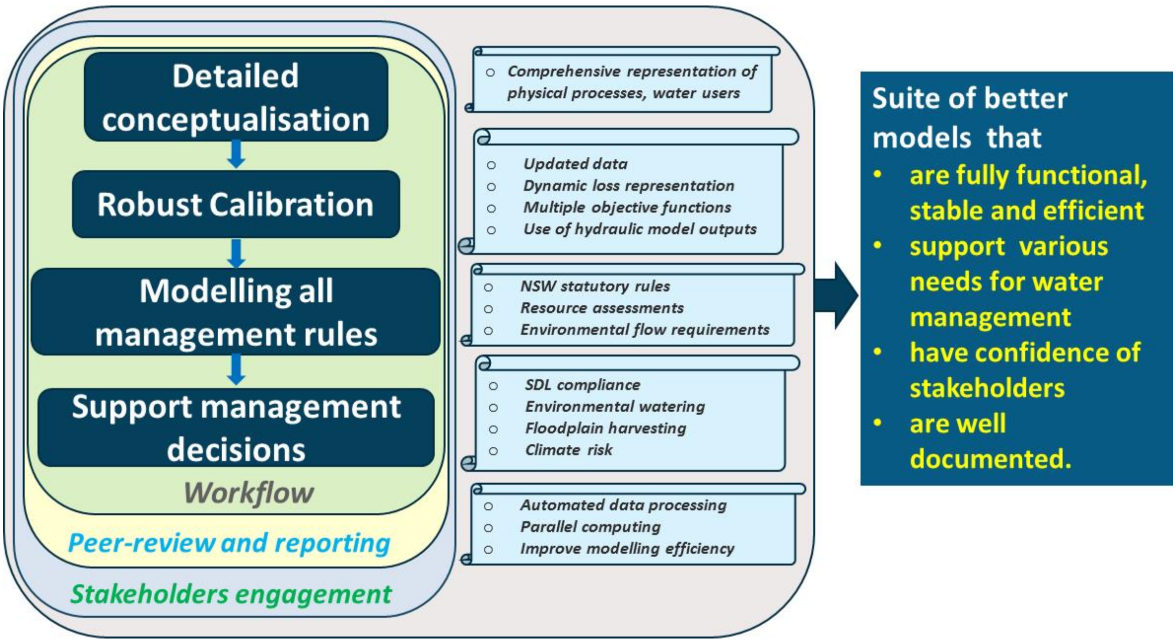

Figure 1. A schematic of the generic approach use in the model building process

Keywords: *River system modelling, water management, NSW*

The Queensland Water Modelling Network – an overview of the benefits of a growing collaborative network *(Part A)*

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Abstract: At MODSIM 2017, the launch and initial results of the Queensland Water Modelling Network (QWMN) were reported with indications of possible next steps. The QWMN aims to help mitigate Queensland Government's exposure to risks identified through an independent review related to possible insufficient and misaligned investment in water modelling research and development to deliver on longer term priorities. These risks were associated with the modelling capability to handle more complex issues like groundwater management or climate change as well as sustained capability of the water modelling sector: government, private and research providers as well as end-users (policy- makers, planners and investment programs).

The QWMN started as a simple network. Lead government agencies with water modelling roles focused on delivering multiple stand-alone projects identified by targeted consultation within the government modelling community. Projects were delivered through a transactional relationship with contractors tasked with delivering products versus building strategic relationships. Communication and engagement was primarily internally focused, linking modellers in different agencies, with little recognition of the QWMN beyond those involved with the projects, either in government or beyond. This was exacerbated by the absence of a website to profile activities and engage more broadly. Outside government, QWMN was seen as a 'closed shop', working with a limited pool of suppliers to deliver mainly Great Barrier Reef modelling related projects supporting Paddock to Reef monitoring, modelling and reporting of investment and practice change outcomes. While there was significant co-investment in some initial projects within government, most projects were underwritten by the QWMN, with limited translation of the learnings and product uptake to mature sector capability.

This presentation will show how the QWMN is evolving to become a more inclusive network. Embracing the water sector can support a more strategic longer-term agenda addressing challenging priorities (e.g. climate proofing models) as well as build capability. The table below compares key dimensions of the QWMN from its launch, current day and desired future state, addressing barriers to collaboration. Critical enablers included: a) consultative reviews of key models and underpinning science; b) a significant investment in enhancing the water modelling capacity (initiated in 2018); and c) a collaboratively-driven Research, Development and Innovation (RDI) Strategy to guide partnerships with stakeholders and investors. This increased awareness and enabled collaborations with new partners within and external to government. A related abstract (Part B): *A collaborative approach to Queensland Water Modelling Network projects* provides practical examples of how the QWMN within its project life cycle is working towards the desired future state, the challenges and direct and indirect benefits.

	2017	2019	Desired future state
Network complexity	Simple – internal to government	Increasingly complex	Complex, integrated hub & spoke project teams
Members	Key government agencies	Extended to research, private and wider government sectors	Broad based membership, influencing broader agendas
Project initiation	Predetermined topics, short-term reactive	Mix of legacy as well as external proposals	Strategic, co-designed, sector priorities
Communication and engagement	Internal – perceived 'closed shop'	External engagement program, website	Curated activities, work with other networks
Governance ownership and control	Qld Government only – bearing risk of investment outcomes	Co–management for key programs, with devolved responsibilities	Shared and devolved activities, with independent hubs
Resourcing and co-investment	Qld Government – Secretariat and RDI investments. Limited external leveraging	Increased co-investment in RDI and capability projects, sharing risks and benefits	Leveraging and co-investment in activities
Model and capability impact	Limited – participating modellers with limited engagement of end-users	Enhanced processes to engage end users, transfer knowledge and collaborative response strategies	Significant – work with partners across the cycle to maximise outcomes

Keywords: *Water modelling, engagement, collaboration, network*

EXTENDED ABSTRACT ONLY

Case examples of collaborative approaches to Queensland Water Modelling Network projects *(Part B)*

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Abstract: The Queensland Water Modelling Network (QWMN) is a Queensland Government initiative to improve the state's capacity to model the quantity and quality of its surface water and groundwater resources. It initiates projects that develop new tools, information and collaborative platforms to support best-practice use of water models, and facilitates uptake of their results by decision-makers. To maximise the impact of QWMN funding, the Network adopts an investment approach based on collaboration and co-investment. In-scope are those activities that address a clear strategic intent (usually reflecting whole-of-government or cross-sectoral interest/agreement); apply an innovative process or approach; involve multiple collaborators; and draw upon the best available science to develop a solution to a defined problem. Activities that reflect 'business as usual' to address operational modelling enhancements are considered out-of-scope.

The presentation will identify case-examples of the major points of collaboration through the project cycle: Scope Definition, Delivery, Governance, Implementation, and Uptake and Evaluation. Co-investment and co-production opportunities are possible at all stages, but more likely to be taken up at the Problem Identification, Scope Definition and Uptake and Evaluation phases. This is illustrated in **Figure 1**. At each point, barriers to success must be addressed including 'an agreed why and way forward'; project leadership, access to relevant knowledge, expertise and conceptual thinking; willingness and time to engage; and the ability to support transfer of project learnings and responses.

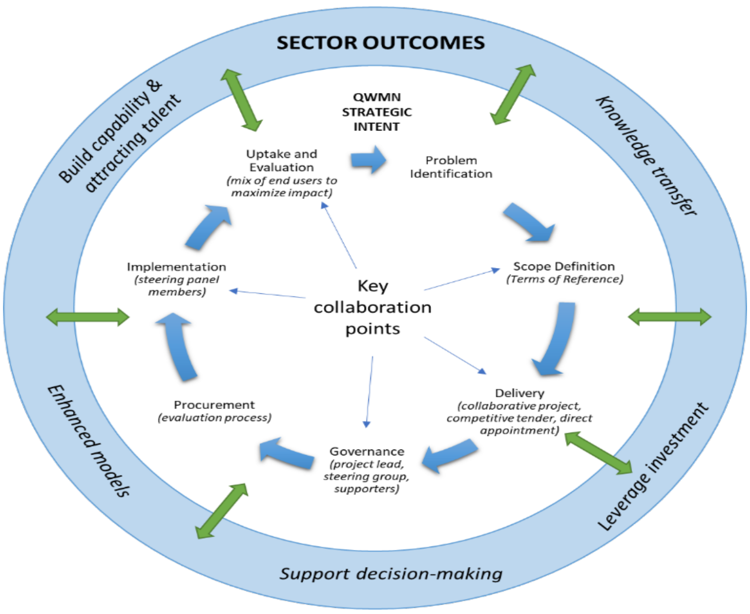

Figure 1. QWMN project cycle highlighting interactions between project phases, sector outcomes, and collaboration's foundational role.

Critical to success is flexibility at all stages, without losing sight of the strategic intent that initially generated the need for action, and the interests of other players and how they might be engaged. Collaboration and co-investment in project design, development and implementation leads to significant benefits for Queensland's water modelling sector – both within and across actors (government, research, utilities, private, not-for-profit). These include, but are not limited to, enhanced application and integration of project outputs (particularly with end-users), an elevated return on investment, and increased capability, knowledge-sharing and talent attraction.

Keywords: *Collaboration, co-investment, project cycle, water modelling*

Critical review of climate change in Queensland water models: Enhancing outcomes

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Abstract: The *Queensland Climate Change Response* outlines the strategies supporting Queensland's transition to a low carbon, clean growth economy and adaptation to the impacts of a changing climate. To achieve this, Queensland Government continues to forge a mature conversation about the implications of climate change and how to ensure the long-term viability of our economy, communities and industries. Through the *Queensland Climate Change Science Plan,* considerable effort has been made to improve baseline information and decision-supports. Computer-based models are valuable tools to inform water allocation decisions, guide water quality investments, and assess the impacts of industry development and proposed planning initiatives on the availability, movement and quality of water resources. However existing/current models may not appropriately or consistently consider the potential impact of climate variability and climate change projections.

The Queensland Water Modelling Network (QWMN) funded project, '*Critical Review of Climate Change and Water Modelling in Queensland,* considered Queensland's ability to account for the impacts of climate variability and climate change projections in its water models. Science, modelling experts and end-users (policy makers, planners and investment programmers) identified the status quo and avenues to enhance capacity. There were four case-studies which identified where specific model's work processes could change, if they were to support additional climate change modelling. Evaluation criteria addressed: the modelling questions; data input and forcing data; conceptual process representation; models components, outputs and their use in decision-making.

The presentation will present the outcomes of the report in the context of the QWMN collaborative framework (summarised below). It will also showcase a case-study demonstrating how the potential impact of climate variability was considered. It will identify the emerging actions, capacity building and collaborations.

Project Phase	Rationale and collaboration under QWMN Climate Review Project
Strategic Intent	Responding to Queensland Government strategic priorities[1], Climate change and variability is identified in the *QWMN Research, Development & Innovation Strategy 2018-2020. Project collaboration* engaged with government stakeholders and separately broader sector at QWMN event to confirm project need.
Problem Identification & Scope Definition Scope Definition	Whilst the climate change implications on water resources and quality have been discussed, the application of consistent approaches within models was not well established. The QWMN collaboratively developed Terms of Reference and consultation requirements with government and sector leaders. Brokering collaborations and network engagement clarified the issues and project scope, considered the need for best available science as well as identifying potential opportunities.
Governance	Collaboration benefits were optimised through engaging strategic partners (e.g. Queensland Government, Bureau of Meteorology, AIMS) and supporters (e.g. Queensland Recovery Authority, Qld Fire and Emergency Services) who championed and informed the project.
Project Delivery & Implementation	Collaboration maximised through competitive open tender which mandated '*integrate collaboration into project design and implementation'* resulting in strong collaborative consortium with review and engagement approaches. Project impact multiplied as collaborators were exposed to regular updates through QWMN community of practice climate change forum and workshop to help test protocols, identify knowledge gaps and shape the final products.
Project Uptake & Evaluation	Collaboration with end users helped develop response plan themes with the aim to improve uptake and help evaluate impact. The project worked with opinion leaders to promote outcomes and integrate into ongoing programs as part of identifying and implementing recommendations.

[1] Advancing Queensland Priorities and Queensland's Science and Research Priorities.

Keywords: *Collaboration, model improvement, climate change action*

Lessons from a water modelling Community of Practice

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Abstract: Communities of Practice (CoPs) are a useful way of bringing together professionals from a range of ages and levels of experience to learn from each other and in doing so pass on practical knowledge through creating relationships that allow champions to emerge and drive innovation and reform. This abstract provides a mid-process assessment of efforts by a team of engagement specialists to design and run a CoP as a way of seeding a self-sustaining and determining group of water modelling professionals in Queensland.

In CoPs, novices and experienced practitioners can learn from observing, asking questions, and participating alongside others with more or different experience (Levine and Marcus 2010). More broadly, CoPs are groups of people who share a concern or a passion for something that they do and who interact regularly to learn how to do it better. The shared concern or passion is the 'domain' of a CoP, the people who interact regularly are the 'community' and the 'practice' refers to how those people learn how to do things better or differently.

The QLD Water Modelling Network (QWMN 2019) has an external engagement program to help build the capacity of water modelling and user expertise in Queensland. To date a series of 4 CoP events have been run, focussing on thematic areas of relevance including skills, urban water management, landscape function and climate change. In addition, a significant sector wide 1.5 day event covering major water policy, planning and management issues that are informed by water models and modelling in QLD was held.

What have we learned so far? Table 1 presents insights and the lessons that we have drawn from them to date.

Table 1. Lessons from running a water modelling CoP after one year

	What's working well	Work in progress and issues to attend to
Events and participation	**Popular events**: using a mix of social media advertising, professional networks and charging a small fee is ensuring strong to full attendance at events **Diversity of participation**: the CoP events have served so far to grow the participation of the private (consulting) sector in relation to the QWMN – consultants make up 25-50% of participants at CoP events, government 9-35% and research 10-26% **Encouraging participation**: including informative presentations at events leads to participants engaging in group workshop activities that can build collective insights	**A busy space**: ensuring that we engage widely with other relevant actors running water-related events in Brisbane to avoid clashes is an ongoing transaction cost **Coping with diversity of interests**: the modelling and user sector is diverse with interests, and there is a need to provide more "hands on" exploration activities for the technically focussed **Cultivating senior support**: if we can develop an appreciation amongst senior executives and team leaders of the value of this network to their organisation they will encourage and support staff participation
Lessons	**Seeds of champions beginning to emerge**: Some professionals are thriving on the opportunity to be outspoken and to challenge the norm and the CoP is enabling them – these professionals may become the champions we need to drive focus that will create CoP longevity **Going from event to output:** through changing resourcing we have tuned our ability to quickly produce informative event write-ups quickly after events	**Working to grow the core**: across this and other CoP activities in Brisbane there is a core group which we need to grow so (i) we have a larger pool from which to cultivate champions who will create the momentum for longevity and (ii) so we don't just rely on the same suspects **Creating outcomes**: CoPs can produce learning and ultimately innovative action – after a year one serious possibility has emerged which now requires cultivation

Levine, T.H. and Marcus, A.S. (2010), How the structure and focus of teachers' collaborative activities facilitate and constrain teacher learning. *Teaching and teacher Education 26: 389-398*

QWMN (2019), https://www.des.qld.gov.au/science/government/science-division/water-modelling-network/ [accessed 30/07/19]

Keywords: *Community of Practice, CoP, water modelling, engagement, collaboration*

A new era for the HowLeaky agricultural systems and water quality model in an open science platform

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Abstract: Most modelling tools in hydrology and agriculture have problems of redundancy, capability of integration with each other, transparency and on-going maintenance. Although there are rare cases of digital platforms to solve these issues e.g. CUAHSIHIS, a requirement remains for an open source and community driven platform that integrates capabilities of model development, dataset management, simulation functionality and technology enhancements. Such a platform should provide the modelling community with facilities for transparent model development and capabilities for sharing and enhancing code, parameter and datasets, regression testing and models for reproducible scientific investigation. The developed platform will make datasets, parameter sets, and codes available to a larger development community to facilitate model growth and develop transparency for a more reliable and useful model.

Currently, reproducibility is a significant issue within modelling communities, particularly in hydrology to address non-static conditions such as climate change.

To address these issues, support provided by the Queensland Water Modelling Network to develop a new platform for the HowLeaky model (www.howleaky.com) has enabled model governance and resource sharing towards a transparent, open science platform for modelling soil water balance and water quality. HowLeaky is a one dimensional, soil water balance model with modules to simulate the quantity and quality of water movement from agricultural land uses at the paddock scale. The modelling environment has been developed on the foundations of the PERFECT model which was strongly influenced by CREAMS and EPIC. HowLeaky is an important asset for operational modelling by the Queensland Government for the Great Barrier Reef Water Quality Report Card, for universities as a teaching tool, and for researchers and consultants to explore interactions between climate, soil, land use and land management. With these enhancements and dependencies, HowLeaky is well placed to transition to a community governed model with software, source code, and experimental datasets being accessible and freely available through a domain website (www.howleaky.com). A hosting framework has been developed with model source code placed on GitHub, while a web-based platform and databases are accessible through the National eResearch Collaboration Tools and Resources infrastructure. Enhancements also include code modifications, automation of the model validation using key datasets, access to parameters of calibrated models, code documentation and ease of model sharing.

In addition, an oversight committee has been convened for peer review of the model development and coordinate future improvements. A model can be run on user selected platforms (on-premise, via website, or cloud) building on previous examples and having access to external databases of climate (from SILO) and soil descriptions (Soil and Landscape Grid of Australia) using Application Programming Interfaces (APIs). The model has a Swagger UI for HowLeaky REST API which can be accessed by third parties for review.

Keywords: *HowLeaky, modelling, open science, reproducible, community model*

What next for the eWater Source Community of Practice?

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Abstract: Source has a strong collaborative history, from its origins in Cooperative Research Centres, through its adoption as part of the National Hydrology Modelling Strategy, and the establishment of eWater to champion ongoing adoption and development and support the community of users. The Source Community of Practice (CoP) has been fundamental to the success of Source as the National Hydrology Modelling Platform. The CoP seeks to bring together Source users, to share ideas, knowledge and expertise, to support the use and ongoing development of the platform and ensure it continues to meet the needs of Australia's water modellers and managers.

The CRC fostered the CoP through initiatives such as; showcasing projects, sharing information resources, facilitating online discussion, coordinating cross-organisational training, working groups, and consensus-building through collaborative production of best practice modelling guidelines.

The eWater CRC ended in 2012 and eWater was established as a Government-owned, not-for-profit company. eWater placed greater emphasis on online community spaces, such as a wiki-based collaborative platform for direct user input and comment, and online spaces to deliver training material, project collaboration, topical discussion groups and live webinars. Greater community ownership of Source was encouraged by letting community experts into eWater's core software development processes through Jira. This increased participation in development and improved process transparency and directly captured user requirements. The Source community also contributed to enhanced functionality by developing plugins (software that allows customised features to be added to existing programs). We encouraged the development of plugins that could be used by all the Source.. The face-face element was not lost, with regular Source application meetings for core government jurisdictions to discuss progress and hurdles to implementation. Recognising the increasing diversity of the CoP, both within Australia and internationally, the annual eWater software conference is now a focal point for exchanging ideas, building networks and exploring opportunities for collaboration.

The CoP continues to be strong, although not all approaches have worked as well as others. We have found that our most successful online platforms are those such as Jira, that directly link to issues with the software, rather than broader online discussion forums. Face-face interaction is becoming less frequent, but participation at the eWater conference increases each year, suggesting that a short-dedicated period of activity may be preferred. Our international user community are more active than domestic users on our social media platforms.

Creating, maintaining and extending a CoP brings a wide range of benefits but is resource-intensive, both in terms of the time required to manage or participate and the costs of supporting CoP activities, such as online platforms and face-face events. The need for efficient use of resources, combined with the increasing diversity of Source models and geographic range of users is making us re-think how we engage the Source CoP. We want to maintain the interest of existing members, build connections with potential members but also involve the broader water management community, who use the outputs of Source models but not necessarily the software.

Keywords: *Communities of Practice, Source, National Hydrology Modelling Strategy*

Towards methods for tracing uncertainty management through a decision support network

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Abstract: The need to address uncertainty is now commonly acknowledged in the modelling community. In a decision support context, fitness for purpose is the guiding principle, but the process of establishing purpose and fitness often remains a black box in practice. We know that modellers use a variety of tools and methods to examine performance, sensitivity, uncertainty, assumptions and pedigree of an analysis. But what do we know about how modellers decide on the techniques to use, and what factors were important in shaping their decisions?

These questions are fundamental to understanding the role of science and modelling in policy making and society, as well improving modelling practice and education. It is not enough to simply point to guidelines, standards or professional judgement. We need to be able to make explicit the processes that modellers actually use: how resources to address uncertainty are prioritised; how uncertainties are actively managed to ensure credibility and legitimacy of results; how standards of proof are (often implicitly) negotiated with end-users; how the modellers' uncertainty management connects with the uncertainty management of data collectors and decision makers...

This presentation introduces a parsimonious framework to make sense of this issue, drawing inspiration from methods in operations research, systems thinking, and science and technology studies. We approach the idea of "uncertainty management" as a process that involves different notions about certainty and uncertainty being pulled into the broader process of modelling and its surrounding activities, including data collection and decision making. A modeller may or may not be aware that they have pulled in a particular notion as part of a particular decision. The notions activated are most visible when they are mobilised in communication within a team, or between modellers and other stakeholders.

Uncertainty management can therefore be traced within a modelling process or a broader decision support network by establishing the pathway taken, the decisions made, and the notions mobilised as part of those decisions. The temporal relationships between steps in a pathway can also be re-formulated as an argument map that provides a snapshot of reasoning, facilitating reflection and debate as to whether uncertainty management was indeed fit for purpose in the case in question.

Keywords: *Uncertainty management, decision support, science and technology studies*

Collaborating successfully in Integrated Assessment and Modelling exercises: personal reflections

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Abstract: Integrated assessment and modelling (IAM) exercises tend to be invoked to address complex problems that intersect several policy sectors, require multidisciplinary expertise, are contentious among interest groups and are characterised by pervasive uncertainty (Zare et al., 2017). It is now accepted that making progress on resolving such wicked issues demands substantial collaboration, at least among scientists, and the participation and engagement of stakeholders so that knowledge is accrued and integrated from different perspectives and values of stakeholder groups are taken into account. How this is done effectively, however, will depend very much on context, including the nature of the problem, the degree of conflict and uncertainty, and the resources available. Guidance on what collaborative and participatory (CAP) mechanisms to use effectively in various situations is therefore difficult and consequently requires attention.

One can however start with several hooks to demystify considerations of CAP mechanism options. The first is to be clear about what constitutes the phases and steps in an IAM project and what questions the team players should ask themselves at each step, thereby motivating answers for their contextual case. Badham et al. (2019) attempt and illustrate this for problems in the integrated water resource management sector. A second hook is to be clear about what factors could be used to characterise success in addressing the given IAM problem (e.g. McIntosh et al., 2011 and Merritt et al., 2017). This would help in considering what CAP mechanisms to use. Hamilton et al. (2019) assist such considerations further by characterising success in eight categories that reflect modelling not only as a technical procedure but also as a social process: project efficiency, model accessibility, credibility, saliency, legitimacy, satisfaction, application and impact. A third hook considers the process as linked to the steps and phases in addressing design of the information flows within steps, design of pathways of interactions and procedures, and execution of a pathway within the planned timeline.

This presentation will not attempt to provide a clear framework on what CAP mechanisms to use, let alone where and when. It will however cover the above hooks. And it will reflect on what CAP mechanisms have played effective roles in specific IAM exercises on which the authors have collaborated. Conclusions on what are essential and useful mechanisms as well as tips on what not to do are presented.

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Keywords: *Collaboration and Participatory (CAP) mechanisms, Integrated Assessment and Modelling (IAM), Reflections*

EXTENDED ABSTRACT ONLY

Collaborating to share water modelling and monitoring information in New South Wales

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Abstract: The NSW Modelling and Monitoring Hub (MaMH) is a knowledge network launched in July 2018 that is led by a state-wide representative Working Group with agreed processes to coordinate and aid information sharing across government agencies and state-owned corporations relating to water modelling and monitoring.

Effective water management is well recognised as a major issue facing all Australian states. NSW encompasses significant spatial and seasonal variability in hydrological conditions. The state supports Australia's major populations in urban centres that are highly concentrated along dynamic riverine/floodplain, estuarine and coastal oceanic shores. Trustworthy and accessible information derived from fit-for-purpose models and data offers government a strong and cost-effective base to inform policy, planning and decision frameworks that is evidence based and scientifically defensible. Information, resource and expertise sharing through the MaMH is benefiting government beyond the resources available within individual agencies.

Knowledge is being developed and shared to strengthen inter-agency capabilities via delivery of a portfolio of Special Projects embracing integrated delivery teams and shared work areas. Regular Working Group meetings, inter-agency roadshows, Open Forums, linkage with like bodies such as the Queensland Water Modelling Network and the expression of Member values all help deliver whole of government knowledge, capabilities and information systems that maximise public value through world-class public sector services for NSW.

In the first year, we have successfully delivered two strategic foundational projects comprising:

1) a state-wide update and summary of water monitoring information; and
2) a state-wide inventory of specialist water modelling activities, capabilities and needs.

Figure 1. NSW Modelling and Monitoring Hub areas of interest

Key findings from over 150 surveyed organisations:

I. difficulties exist in achieving awareness of water models and information held in multiple sources;
II. untapped synergies existing from variable skills and capabilities across organisations;
III. incomparable budget information exists across organisations; and
IV. underutilised collaboration platforms exist that could be better used to share models and information.

The presentation will provide details of state-wide capabilities, barriers and needs to enhance collaboration.

The current MaMH membership (restricted to state agencies and state-owned corporations with interests in water) has been effective in establishing whole of government priorities. Based on the findings of the first two foundational projects, we have identified the need to develop guidelines for essential water modelling and monitoring metadata and to better define systems and processes via a series of carefully designed site-specific pilot case studies that will enable the implementation of state-wide federated collaboration tools. We propose to involve other tiers of government, universities and industry bodies more closely as sharing tools and processes are established in coming years.

Keywords: *Collaboration, modelling, monitoring, data sharing*

A collaborative review process supports better outcomes from environmental modelling

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Abstract: Environmental modelling is used to support development planning, environmental policy, natural resource management, and environmental impact assessment. In all these contexts, it is important that the models have been carefully vetted and are suitable for the application at hand. Modelling clients often commission peer review by independent experts to ensure that the models that they rely upon are in line with best practise and can be defended when challenged.

Traditional review processes occur after model development and evaluation has been completed and documented. Here, we discuss the alternative of a collaborative peer review that is conducted alongside model design, development and evaluation, with regular communication between the client, review team and modelling team. The experiences of the UNSW modelling team, the CSIRO/AIMS review team and the client, Hunter Water, are each discussed separately.

Advantages of the collaborative review process included (for the review team) the opportunity to intervene early and suggest ways to avoid potential problems before too much had been committed to a particular approach, and reduced potential for conflict with the modelling team when concerns were raised; (for the modelling team) opportunity for collegiate open dialogue and the opportunity to understand critical issues for the reviewers and avoid wasting resources by guessing what reviewers would focus on; and (for the client) reduced potential for unpleasant surprises on review of the final models, and the opportunity to learn more about the modelling process to better inform their decisions relating to model development as well as their future use of the models.

Potential disadvantages included a more expensive review process (due to the requirement to engage the review team throughout the development process) and increased risk that the independence of the review process could be compromised if not carefully documented. In this case study, however, all parties were satisfied with the outcome.

Keywords: *Review, receiving water modelling, water quality, best practice modelling*

EXTENDED ABSTRACT ONLY

AWRA-CMS: A framework for hydrological model development

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Abstract: Australia has scarce freshwater resources and is expected to become drier under the impacts of climate change. To be able to effectively manage and mitigate the effects of scarce or depleted water storages there is a need for up to date water resource information. The Bureau of Meteorology has developed a national hydrological model to fulfil this need, and the AWRA Community Modelling System (AWRA-CMS) is the software framework that is used to run it.

The AWRA-CMS modelling system contains the tools for model implementation, model run, model calibration, model validation, data assimilation, and analysis. These components are designed using object-orientated principles and the latest software paradigms, with flexible adaptable interfaces written in Python for rapid implementation, development, prototyping and deployment. The software repository is hosted in GitHub in order to provide access and collaboration features to the wider community (https://github.com/awracms/awra_cms). Users are thus encouraged to contribute to the repository, which in turn strengthens modelling outcomes. The current community of users hail from universities, government organisations and consulting firms.

To meet the demands and challenges of high resolution hydrological modelling, the AWRA-CMS employs the use of scalable high performance computing and data management techniques. The software framework is designed to be platform agnostic with a configurable setup for any platform. This means computationally demanding tasks such as calibrating and validating a large-scale hydrological model, can be run in very short timeframes, resulting in reduced model development and deployment timelines. Examples of common workflows such as model calibration and validation exist in the repository in the form of Jupyter notebooks which are easy for a novice programmer to use, combine code, documentation and visualisations, and are designed for self-directed learning.

We present a model development workflow using the AWRA-CMS framework. The steps detailed in the workflow include: (1) Model implementation/alteration, a toolset which allows the user to modify the model using a python wrapper such that programming proficiency is no longer a barrier. (2) Model calibration, a toolset which provides a user-friendly interface for model calibration, with which a user can specify different optimizers, such as: Borg multi-objective evolutionary algorithm, shuffled complex evolution method, and different objective functions, such as: Nash-Sutcliffe efficiency index, Kling-Gupta efficiency, to calibrate a set of parameters. (3) Model validation, a toolset which provides a user-friendly interface to validate the (calibrated) model, where the user can choose from several different hydrological metrics. (4) Model analysis, a toolset which provides a user-friendly interface for statistical analysis of model fields. This workflow is used to deploy updates to the national hydrological model, where the model update is deemed suitable once it is successfully benchmarked against a suite of hydrological models, including the previous version of the model.

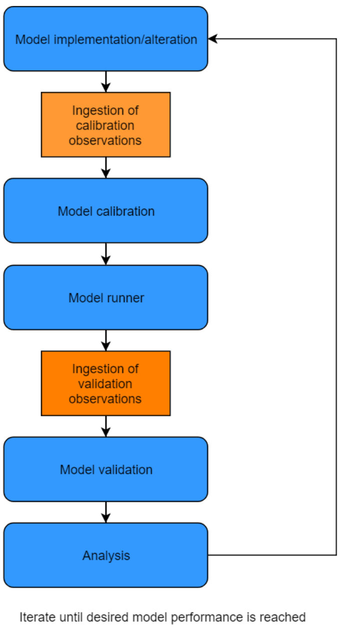

Figure 1. Model development workflow

Keywords: *Model development, software framework, hydrologic model*

The collaboration model delivering land use information for Australia

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Abstract: To collaborate is to work together towards a common goal. A collaboration model is the framework that facilitates this cooperation. The Australian Collaborative Land Use and Management Program (ACLUMP), overseen by the National Committee for Land Use and Management Information (NCLUMI), was established in 2000 and is recognised as an exemplar in cross-jurisdictional natural resource coordination. ACLUMP is a partnership between state, territory and federal government land management agencies, providing consistent land use information across the whole continent. ACLUMP's collaboration model:

1. Recognises the different roles and responsibilities of state and federal agencies within a national context.
2. Identifies common strategies and priorities to facilitate joint investment.
3. Encourages a culture of regular meetings to discuss land use policy and planning issues and to share technical expertise.
4. Responds to emerging issues and technological advances.

Collectively, ACLUMP has developed a national approach to the mapping and classification of Australia's land use. Technical standards are applied by all parties in the production of 'national' and 'catchment'-scale land use spatial information products accessible through jurisdictional data portals or the ACLUMP website.

In an environment of short-term funding and regular organisational restructuring, ACLUMP has persisted. ACLUMP's experiences could be beneficial to other multi-organisational and inter-jurisdictional groups wishing to establish a successful collaboration model.

Keywords: *Land use, spatial data, national standards, Australian Collaborative Land Use and Management Program*

Constructing customized modelling guidelines: a Participatory Integrated Assessment and Modelling example

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Abstract: As scientific modelling and integrated assessment have matured, a number of best practice guidelines have emerged. While standard guidelines play an important role in setting expectations for repetitive modelling tasks, many problems require a flexible, adaptive approach, meaning that analysts cannot simply follow a single guideline, but rather have to draw on several to construct a process to address their problem. New combined guidelines or meta-guidelines often add further complexity rather than solving the issue. In this paper, we describe two simple ideas to combine multiple guidelines in a way that provides a customizable modelling process: "pathway diagrams" and "ID cards". The former involves thinking of an analysis process in terms of a unique "pathway", divided into a set of steps, including decision forks and points for reflection and iteration. This pathway provides a structure within which steps from guidelines can be inserted. The second idea involves identifying steps recommended within guidelines and annotated them to link them to an "ID card" for that step. Each ID card then provides a quick summary of what has been said about a step across multiple guidelines. While these ID cards can pull in information from a variety of sources, they remain an individual/group's personal summary of the state of knowledge about a step, providing a common language and point of interaction for thinking about and discussing what steps can be inserted into a pathway and why. We provide an example pathway, its steps and an example of the ID card. Specifically, we build and demonstrate a Participatory Integrated Assessment and Modelling pathway drawing on key, highly cited articles. It is hoped that the pathway diagram will help implement the idea of modelling as an adaptive spiral process, containing several iterative loops to reach a fit for purpose model and agreement between stakeholders.

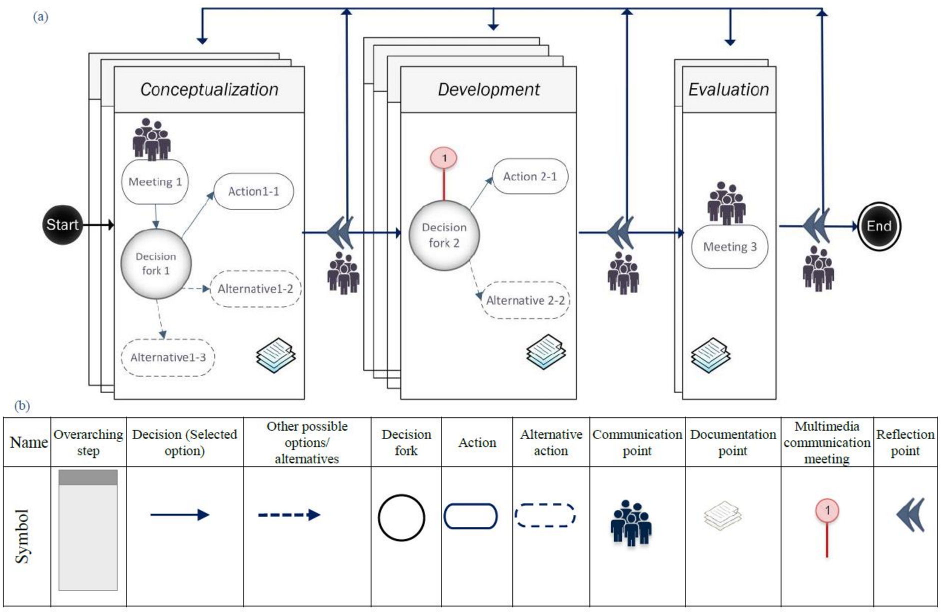

Figure 1. A pathway example (a) and legend (b), demonstrating the use of the pathway diagram components (Zare et al., 2019)

Keywords: *Integrated modelling, participatory modelling, Pathway, ID cards*

Dispersive distortion of pulling-dominant tsunamis caused by outer-rise earthquakes and submarine landslides

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Abstract: While tsunamis are dispersive water waves, effects of dispersion are often neglected in tsunami hazard maps for earthquake-generated tsunamis. This is because spatial dimensions of the earthquake-generated tsunamis are much greater than the water depth and that dispersive effects are generally small. Another reason of the neglect of the dispersion is due to high computational coast associated with dispersive tsunami calculations. However, in recent years, this would be no longer a problem thanks to advances in computing performance. The third and the most important reason is that the non-dispersive calculations tend to predict higher tsunamis than dispersive calculations. Although the non-dispersive model may overpredict the maximum tsunami height, this conservative approach is acceptable in disaster management for saving lives and properties.

But this study demonstrates that the non-dispersive model does not always provide larger tsunami height than the dispersive model in some cases. According to our numerical simulations, tsunamis caused by outer-rise earthquakes and submarine landslides are such cases. For the numerical simulations, we used open dispersive tsunami software, JAGURS, parallelized by OpenMP and MPI (Baba et al., 2015). JAGURS also includes effect of elastic loading (i.e., tiny deformation of the earth due to tsunami load) that enables accurate predictions of dispersive far-field tsunami waveforms (Baba et al., 2017). Source codes of JAGURS can be downloaded via GitHub (https://github.com/jagurs-admin/jagurs).

Outer-rise earthquakes are caused by high-angle normal faults under the deep ocean. The ocean bottom is displaced to subsidence in a narrow area by the earthquakes, and that results in generation of pulling-dominant tsunami with short wavelength. An outer-rise earthquake of Mw7.3 in 2010 along the Bonin Trench accompanied with moderate tsunamis. The tsunamis were recorded by Deep-ocean Assessment and Reporting of Tsunamis (DART). At DART 21413, a tsunami waveform from dispersive tsunami (Boussinesq) calculations predicted the observed tsunami waveform better than non-dispersive tsunami (shallow water) calculations. In comparison, the maximum height of the dispersive tsunami waveform is slightly larger than that of the non-dispersive tsunami waveform (Fig. 1a).

Numerical experiments using a two-layer flow model predicted that shapes of tsunamis were generated asymmetrically by submarine landslides. Pushing-dominant (positive) tsunami waves propagate in the direction of the submarine mass movement, and pulling-dominant (negative) tsunami waves propagate in the opposite direction. Both types of waves are deformed by the effect of dispersion. For pulling-dominant wave, the maximum tsunami height of the dispersive calculation is approximately two times larger than the non-dispersive calculation (Fig. 1b).

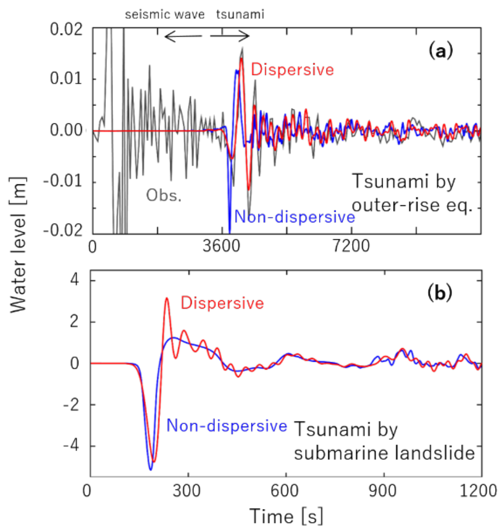

Figure 1. Comparison of tsunami waveforms. (a) The 2010 Bonin tsunami recorded at DART21413, (b) Submarine landslide tsunami in numerical experiments.

Keywords: *Tsunami, dispersion, numerical simulation, outer-rise earthquake, submarine landslide*

Developing a numerical simulation model for a meteorite impact tsunami

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Abstract: Tsunami induced by earthquakes, submarine landslides, volcanic eruption in submarine, volcanic pyroclastic flow in coastal area and meteorological phenomena is one of the most devastating natural disasters. A meteorite impact into the oceans spawn large tsunami depending on the size and velocity of the meteorite and the sea depth at the location of the impact as well. However, we do not have a numerical simulation model to reproduce both of meteorite impacts and tsunami propagations yet. We have started to develop a new numerical model to simulate tsunamis generated by the meteorite impact by combining iSALE (Wünnemann et al., 2006, *Icarus*) for simulating impact of meteorite into the ocean and JAGURS (Baba et al., 2017, *Ocean Modeling*) for simulating tsunami propagation. The iSALE is a multi-material and multi-rheology shock physics code for simulating impact phenomena. This is widely used for planetary science research fields. JAGURS is an open source parallelized tsunami simulation code to calculate tsunami waveforms, tsunami height and inundation on land by solving two-dimensional non-linear long-wave equation with Boussinesq terms. In order to combine these two simulators, we set sea-floor deformation, sea-surface disturbance and propagation velocity obtained from iSALE as the input of JAGURS in the restart files. In order to perform tsunami hazard assessment for the worldwide coastlines, fine spatial resolution digital elevation models (DEM) are needed. GEBCO_2014 and GEBCO_2019 which have 30 arc-sec (about 1 km) and 15 arc-sec (about 500 m) respectively are possibly used for calculating tsunami propagation whole the world. However, it is not enough spatial resolution to represent tsunami height and inundation along the coastline, we then need to prepare DEM which has more fine resolution. Therefore, we tried to create DEM combining ASTER GDEM version 3 (Fujisada et al., 2012, *Remote Sensing*) and GEBCO_2019 Grid. ASTER GDEM has one arcsecond (about 30 m) spatial resolution and covers land between 56S and 60N latitude as a topographic data. GEBCO's gridded bathymetric data will be upgraded as 100 m resolution in the Seabed 2030 project. Furthermore, in order to perform real-time meteorite impact tsunami, we consider the way of automatic detection of meteorite impact using the recode of the highly sensitive seismograph network in real-time.

We first investigated meteorite impact tsunamis using simplified cavity curves (Ward and Asphaug, 2000, *Icarus*) with developed JAGURS built-in. We then investigated the tsunami generation using iSALE code for creating tsunami source model depending on the meteor size, the velocity of impact and the depth of water at the impact location to obtain cavity size, height of rim and expansion velocity. Finally, we construct a new numerical model of meteorite impact tsunami combining iSALE and JAGURS.

We gratefully acknowledge the developers of iSALE, including Gareth Collins, Kai Wünnemann, Boris Ivanov, H. Jay Melosh and Dirk Elbeshausen. Data analysis and visualizations of iSALE were carried out on PC cluster and computers at Center for Computational Astrophysics, National Astronomical Observatory of Japan. This work was partially supported by JSPS KAKENHI Grant Number JP18K04674 and JP19H02409.

Keywords: *Tsunami, JAGURS, meteorite impact, iSALE*

Validated flood modelling for the Copiapó basin in Chile

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Abstract: The Copiapó basin in the Atacama region of Chile has a dry climate with very low annual rainfall. Despite this, the city of Copiapó has experienced significant flood and mudflow related disasters in recent years. A flooding event in March 2015 killed 31 people and more than 5,000 homes were severely affected. The key reason for the flood was the unusually high rainfall in upstream catchments leading to flash flooding and sediment pick-up including mud and debris. The future potential effect of climate change may be to increase the frequency and impact of these types of events. This has caused the authorities to prioritise planning for such events better going forward. The water authority of Chile (DGA) have collaborated with CSIRO to develop flood modelling capabilities in order to provide evidence-based advice to support future adaptation related planning activities.

Over several years CSIRO have developed a flood modelling software called Swift (https://research.csiro.au/swift/) and applied it to flood modelling projects for cities across Australia. The core of this software consists of a finite volume based Shallow Water equation solver which is designed to run on modern graphics processing unit (GPU) hardware. The software models scenarios involving catchment-based flooding, rainfall and coastal inundation. Swift is suitable to model flooding events for the city of Copiapó for purposes such as risk assessment, urban planning and assess suitability of evacuation zones. Additionally, Swift has integrated capabilities for including flood adaptation measures so their effectiveness can be quantified. By running ensembles of adaptation design variants for a given scenario, the minimum design for effectiveness may be determined. Conversely, by running ensembles of scenarios for a given adaptation design, the threshold scenario for adaptation effectiveness can be determined. These use cases rely on the software having been validated against historical flooding events for the region. This paper outlines the Copiapó basin model and the process undertaken to validate the Swift software using data from the 2015 Copiapó flood event.

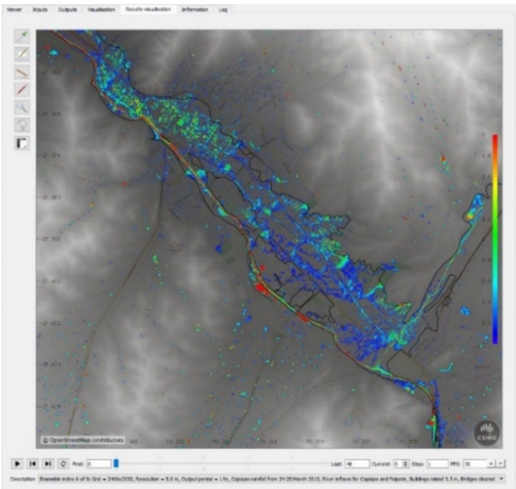

Figure 1. Swift screenshot of a Copiapó simulation showing maximum inundation height ranging from 0 metres (blue) to 2 metres (red) masked to only display inundations above 0.1 m.

The model of the Copiapó basin was constructed by compositing multiple digital elevation model rasters (DEMs) together with resolutions ranging from 30 metres down to 5 metres. Land use classification data was mapped to corresponding Manning roughness coefficients in each simulation cell. Polygons of all the buildings within Copiapó were used to modify the DEM and include them in the simulation. Bridges along the rivers were removed from the DEM to allow unimpeded flow of the water along the river channels. Bridges that were blocked by debris during the flood event had the corresponding DEM cells raised to the height of the bridge surface. Two-hourly rainfall data was obtained from the local rainfall station in Copiapó and was used directly in the simulations. Determining the river inflows for the simulation was more difficult as the extreme flood event had overwhelmed the flow gauge stations in the region. Estimates of river inflows were determined by running an ensemble of simulations for different inflow values and finding when the simulated flood extent matched the historical flood extent data. This was observed to agree with the estimated river flow values from a published report and ultimately used for the validation case. Validation was achieved due to good agreement between the simulation results and the 2015 flood extent data, building damage data and mud height data.

Keywords: *Flood modelling, validation, historical flooding, adaptation*

Developing a flood inundation emulator based on two-dimensional hydrodynamic modelling results

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Abstract: Towards an improved flood management strategy, floodplain inundation modelling is considered as an essential part of river basin management for engineering, ecological and environmental perspectives. While hydrodynamic model is a powerful tool for flood inundation modelling, It takes several months for input data preparation, model configuration and calibration. Flood inundation emulator is a useful alternative of comprehensive flood inundation modelling for a quick estimate of inundation area against catchment runoff. This information is crucial for flood forecasting and flood risk management. This paper presents results from flood inundation modelling using a flexible mesh (irregular grid) hydrodynamic model (MIKE21 FM) and the relationship between catchment runoff to floodplain inundation for the Fitzroy catchment in Western Australia. The hydrodynamic modelling domain covers an area of 35,000 km^2 and consists of approximately 2.0 million triangular mesh with minimum and maximum grid size of 48 m^2 and 8.1×106 m^2, respectively. For a computational time step of 5 sec, the model takes approximately 2 days of computer time (GPU machine) for the simulation of 40-day flood event which is about 5 times faster than a regular grid model.

The inundation emulator was developed by relating inundation area, simulated by the hydrodynamic model, to flood discharge. Streamflow data from the three upstream gauges (802005, 802137 and 802203) that flow directly into the hydrodynamic modelling domain were aggregated. This aggregate was used to produce a time series of inflows into the modelling domain. Two measures, computed from the flow data, were compared with the flooding extent data. The first was total volume over the event period, the second was peak flow during the event period. These were graphed against maximum inundation area. In both cases, there was a clear relationship between inflow and inundation area. Of the two measures, peak flow during event period was determined to give the best relationship and chosen as the measure for use in the regression model. Having chosen peak flow as the measure, three methods (linear, polynomial and exponential) of regression were tested to capture the relationship between peak flow and inundation. Among the methods, a power curve in the form of $A=bQ^n+c$ was used to calculate inundation area (A) where, Q represents daily stream flow, and b, c and n are fitted parameters. The parameters were estimated using a least square error method. Once the model had been fitted, it was applied to stream flow values to estimate inundation area. Each streamflow value was treated as the peak flow of a hypothetical flooding event, producing a corresponding time-series of maximum inundation area. The emulator produced a good estimate of hydrodynamic model simulated inundation area (Figure 1) and the fitted parameter are 0.54, 36 and -745 for the n, b and c respectively. A correlation coefficient of 0.95 was attained for the Fitzroy catchment and the emulator was found valid for the total inflow of equal or greater than 515 m^3/s.

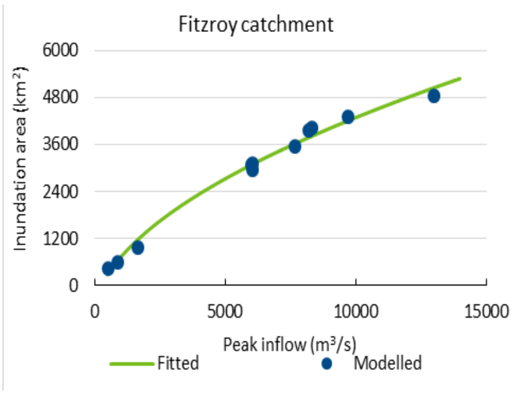

Figure 1. Hydrodynamic model simulated inundation area and regression-based flood emulator for the Fitzroy catchment

Keywords: *Inundation modelling, MIKE 21 flexible mesh, LiDAR*

Urban flood hazard analysis in present and future climate: a case study in Ha Tinh city (Vietnam)

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Abstract: In the trends of climate change and increased urbanization all over the world, adequate attention needs to be given to urban flood hazards. Located in Southeast Asia, Vietnam is identified as one of the countries in the world that is most vulnerable to climatic changes. Ha Tinh city, located in the North Central region of Vietnam - faces a combination of several factors causing a serious increase of the urban flood problem. These factors include: frequent occurrence of tropical typhoons, characterized by extreme precipitation amounts; located in a low delta region (about +2.5m above the mean sea level) and close to the coast (about 12km from the coast) leading to a strong impact of the tidal regime on the city's drainage capacity. Other factors are the urgent need to upgrade the storm sewer system given its insufficient capacity, and the poor urban planning and management system.

In the recent years, a rapid urbanization trend has been observed in Ha Tinh city. In the city suburbs, huge areas of agricultural land were converted to urban and industrial areas. In the inner city, most of the area has become residential and infrastructural areas. Urbanization leads to an increase in the fraction of the impervious surfaces and consequently increase the amount of storm water directed to the urban combined sewer system. Finally, this cascade causes more flooding in the city. Ha Tinh city is ranked fourth among all cities in Vietnam vulnerable to climate changes, e.g. intensification of extreme precipitation amounts and sea level rise. In Vietnam, several studies have been conducted on urban flooding in the larger cities along the Red River and the Mekong River. However, smaller cities such as Ha Tinh city, are largely unexplored, mainly due to the lack of data on infiltration, imperviousness, Manning roughness coefficient, etc., but also on climate change and urbanization data.

In this study, the urban drainage system of Ha Tinh city is represented by a 1D/2D coupled urban-drainage/overland flow model (MIKE URBAN). The model has been calibrated and validated for 4 historical flood events by means of observed inundation depths and referenced media photos. The uncertainty in the data and its implications for the infiltration, imperviousness and Manning roughness coefficient have been accounted for in order to improve the model performance. Furthermore, new insights on the future climate variables were obtained after statistical downscaling by applying a quantile perturbation approach on a large ensemble of CMIP5 global climate model runs for all four RCP scenarios. The SOUTH ASIA-CORDEX regional climate model runs were also considered. Changes in extreme rainfall intensities and evapotranspiration based on RCP scenarios were analyzed and together with the urban sprawl scenarios, present and future pluvial flash flood hazard maps of Ha Tinh city were produced and compared. These maps are considered as a background information in the design and the evaluation of potential adaption measures. The results of this study have led to new insights in the city's pluvial flash flood hazard for different sprawl scenarios and for current and future climatic conditions. The results moreover provide valuable information for spatial planning, disaster preparedness and adaptation.

Keywords: *Urban flooding, statistical downscaling, quantile perturbation method, CORDEX climate model runs*

Incorporating dependence in Intensity-Frequency-Duration curves: Flood risk estimation for civil infrastructure systems

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Abstract: Conventional methods for generating Intensity-Frequency-Duration curves tend to focus on pointwise estimation of Intensity-Frequency-Duration (IFD) relationships, and thus lose information on the storm-level spatial dependence between extreme events. This study presents an approach to IFD estimation based on max-stable theory that embeds storm-level dependences across both space and storm-burst duration. This leads to Intensity-Frequency-Duration-Dependence (IFDD) curves across a spatial domain that explicitly holds information on:

- Joint dependence both across space and across different storm burst durations, which enables joint probability calculations such as for civil infrastructure systems (e.g. road and rail networks) where failure at any one location compromises the performance of the overall system;
- Conditional dependence both across space and across different storm burst durations, which enables calculations of the probability of flooding at specified locations conditional on other locations being flooded such as might be required for evacuation route design; and
- Areal reduction factors, including changes to spatial storm extents as they become increasingly extreme.

Importantly, the inclusion of spatial dependence between different storm burst durations enables estimation of relationships between extremes across multiple catchments with different critical times of concentration.

This presentation will demonstrate this framework for a case study of a highway upgrade, made up of five bridge crossings for which the upstream contributing catchments each have different times of concentration. The results show substantial differences between conditional and unconditional extreme rainfall and flood discharges, and also demonstrate the role of spatial dependence in determining the overall probability of system failure. These results highlight the potential benefits of explicitly focusing on overall system design considerations, rather than focusing on each element of the transport network in isolation.

Keywords: *IFD curves, max-stable modelling, areal reduction factors, statistical dependence, joint probability*

EXTENDED ABSTRACT ONLY

Tsunami data assimilation of offshore ocean-bottom pressure gauge records for real-time forecasting

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Abstract: Tsunami observations in the ocean-bottom environment have advanced significantly in recent years for reducing tsunami disasters by analyzing these data in real-time. In addition to the Deep-ocean Assessment and Reporting of Tsunami (DART) system, which is distributed worldwide, multiple regional dense real-time tsunami observation networks are being developed particularly around the Japanese Islands. Detection and modelling of the offshore tsunami in real-time by using ocean-bottom stations are crucial for prompt warnings before it arrives at the coastline. Various methods have been proposed to achieve the real-time warnings of tsunami attacks by estimating tsunami or earthquake source as an initial condition. However, these methods inevitably affected by the uncertainties of source parameter estimates.

Recently, we proposed a data assimilation approach as an alternative to real-time tsunami forecasting method [Maeda et al., 2015, doi:10.1002/2015GL065588]. This approach tries to fit the whole tsunami wavefield, including tsunami height and flow velocities, based on dense observation. At every small-time step, numerically-forecasted tsunami waveforms at stations are compared with observation and corrected if necessary with previously-calculated spatial weight functions. The corrected tsunami wavefield, or data-assimilated field, is again used as an initial condition for forecasting the tsunami at next time step, which enables us to apply the data assimilation successively to the real-time continuous tsunami observation. This approach was tested against the hypothetical 2011 Tohoku earthquake tsunami with S-net ocean bottom pressure gauge and succeeded in recovering tsunami wavefield quickly. As this method estimates tsunami wavefield in a wide area, one can use it as an initial condition of tsunami forecasting at coastline anytime if necessary. A major characteristic of this approach among many other methods is that it does not explicitly use any earthquake source data, such as magnitude, fault mechanism, and rupture process. Thus, the method is free from the estimation uncertainties of the earthquake source; thus, it is appropriate for real-time monitoring.

On the other hand, the data assimilation approach requires relatively large computational resources and very dense tsunami observation network. These drawbacks are now being settled by developing new techniques. Wang et al. [2017, doi:10.1002/2017GL075307] found that forecasting tsunami at points of interests from the tsunami wavefield assimilation is mathematically equivalent to the sum of the Green's functions of tsunami originated from stations, which dramatically accelerates the forecasting time with keeping its accuracy. Although the original data assimilation requires that the interstation separation be shorter than the characteristic wavelength of the tsunami, Wang et al. [2019, doi:10.1029/2018GL089030] proposed to set virtual stations between sparse network stations with an assumption of 1D tsunami wave propagation between them; they found this approach helpful for improving accuracy of tsunami forecasting even with sparse station network. In addition to the numerical-simulation-based experiments using hypothetical observation, we also succeeded in applying the data assimilation approach to offline/online real-world tsunami data [Gusman et al., 2016, doi:10.1002/2016GL068368; Wang et al., in press, 10.1029/2019JB018056].

One of the major remaining issues in tsunami forecasting by methods which include the data assimilation is the dynamic/static pressure change due to the seismic ground motion and coseismic deformation. As ocean-bottom pressure gauges detect tsunamis via pressure change, such disturbances seriously affect the data obtained nearby the earthquake source. Seismic ground motion directly oscillates the pressure gauge instruments, and a part of the seismic waves converted to the ocean-acoustic waves also may affect the observation significantly, particularly at the earlier time just before the earthquake. Since we still have very little pressure gauge data recorded nearby large earthquakes, various tests of tsunami forecasting using large-scale numerical simulation is indispensable for improving the quality of real-time tsunami forecasting.

Keywords: *Tsunami, real-time forecasting, ocean-bottom pressure gauges, data assimilation*

Impacts of the representation of stream network and spatial resolution on the simulation of large-scale floods using a 2D flexible mesh hydrodynamic model

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Abstract: Hydrodynamic modelling is commonly used to simulate flood inundation for disaster preparedness, environmental conservation, and supporting flood-related decision-making in general. In the past, the use of detailed hydrodynamic models has been limited to modelling short river reaches or small catchments due to high computational and data demand. With advances in computing power and increasing data availability, the application of hydrodynamic models to large catchments or basins is becoming more achievable. However, such applications are usually implemented at coarse spatial resolution (>100m) or with a simplified representation of topographical details. While numerous studies have been done to investigate the impacts of spatial resolution and representation of topographical details on the simulation of reach-scale floods using 2D gridded models, such analyses are rare for modelling large-scale floods using 2D flexible mesh hydrodynamic models. Flexible mesh models allow the use of finer spatial resolution (<100m) in areas of interest and coarser spatial resolution in areas that are rarely inundated by floods. With the proper creation of a model mesh, it is possible to reduce the computational elements, and thereby, the computational costs of using a hydrodynamic model for larger domains.

In this study, the 2D MIKE Flood flexible mesh model is used to investigate the impacts of the representation of stream network and spatial resolution on the simulation of floods in a section of the Middle Darling Basin (~5100 km^2). Flexible mesh models were created by assigning fine spatial resolution along streams (max of 1500 m^2) and coarse spatial resolution elsewhere (max of 150000 m^2). The stream networks were automatically generated using the Spatial Analyst Hydrology Tools of ArcGIS from DEMs of varying resolution (5m. 10m, 30m) which were derived from a 1m LiDAR DEM of the basin. For each DEM, three types of stream networks representing varying stream orders (see Figure 1) were generated: (O1) main streams only, (O2) up to secondary level tributaries, and (O3) up to tertiary level tributaries.

It was found that the representation of the stream network greatly impacts the simulated flood inundation, especially during the early stages (rising limb) and receding stages (falling limb) of the flood (hydrograph). Compared with the models which represented the tertiary level tributaries (O3), the models which represented main streams only (O1) result in more flooded area around main streams and slower flows along streams. The impacts of the spatial resolution of the DEM from which the stream networks were derived were not as significant as the impacts of the representation of the stream network.

These results indicate that the level of representation of stream network in a model may affect several flood parameters such as flood extent, duration, and velocity. The results also suggest for the selected basin, a relatively coarse (up to 30m) DEM may be used to derive a detailed stream network and still capture the inundation patterns adequately. These findings are relevant to flood modellers who wish to apply a 2D hydrodynamic model at a large scale but are short of computational resources. Overall, the findings of this study are also relevant to researchers, environmental water managers and policymakers who wish to apply a hydrodynamic model to a large floodplain.

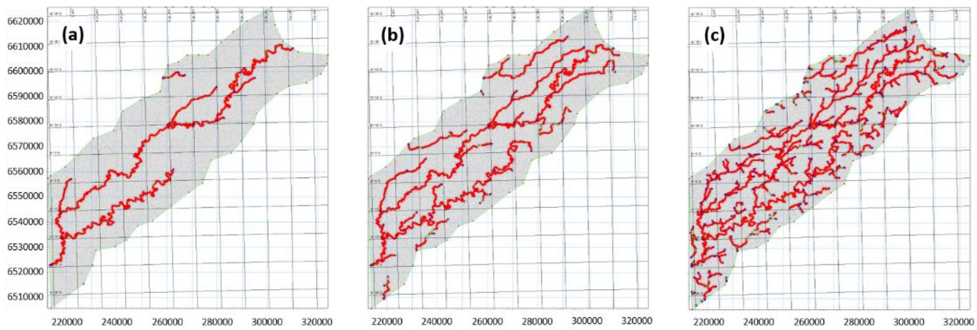

Figure 1. Three stream networks representing the (a) main stream, (b) up to secondary level streams, and (c) up to tertiary level streams which were derived using a 5m DEM

Keywords: *Stream network, spatial resolution, 2D flexible mesh hydrodynamic model*

Solving the fully non-linear weakly dispersive Serre equations for flows over dry beds

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Abstract: The Serre equations provide an excellent non-linear dispersive model of shallow water flows, but a particular challenge is the transition from wet to dry. The Serre equations can be written in conservation equation form, which is similar to the Shallow Water wave equations (SWWE), together with an auxiliary elliptic equation for the depth-averaged horizontal velocity. This leads to opportunity to use numerical methods designed for the SWWE which can deal with problems with large gradients and are designed to deal with dry beds. Here we present such a finite volume method that can robustly and accurately approximate flows involving flow over dry beds. The numerical method is validated against analytic solutions and forced solutions and shown to be accurate and well-balanced. Finally, the method is validated against experimental results [C. Synolakis, Journal of Fluid Mechanics, 185 (1987) pp 523-545] for the run-up of a solitary wave on a linear sloped beach. The results are shown in the figure.

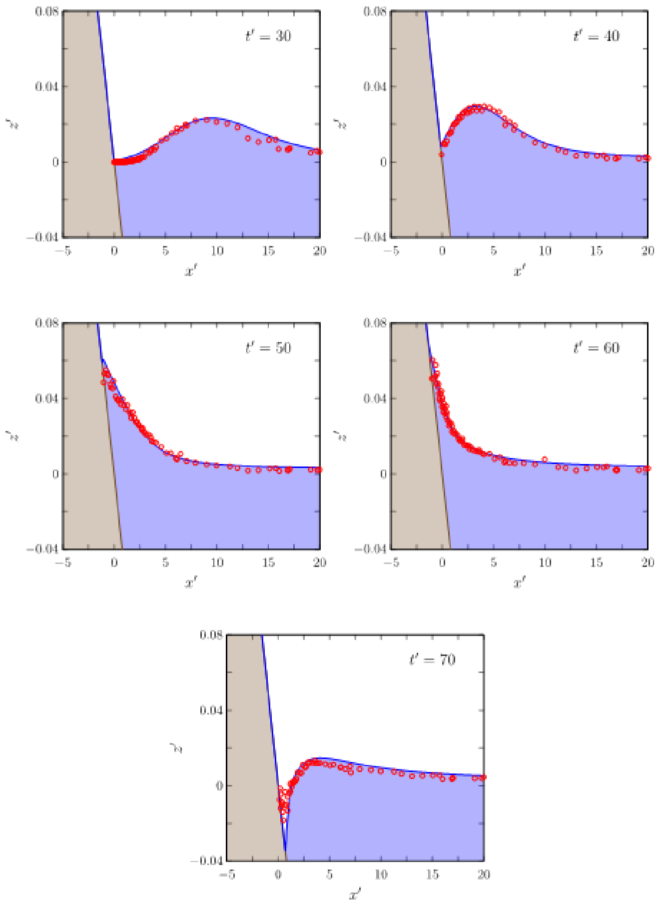

Figure: A comparison of the water surface profile for Synolakis's linear beach runup experiment and the numerial experiment (blue) over the bed (brown) at various times.

Keywords: *Serre equations, dispersive models, dry bed*

TRI-based tsunami source inversion

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Abstract: Precise constraints on the tsunami source are crucial to improve the accuracy and reliability of tsunami forecasts. Most source estimation methods utilize precomputed databases composed of pairs of elemental sources and their waveforms at observation sites. The waveforms are usually obtained by numerical simulation. Representative tsunami sources can be selected from the database based on the similarity of their waveforms with observed ones. The tsunami source can also be synthesized as a linear combination of elemental sources, where the mismatch between observed waveforms and synthetic ones is minimized. If a combination of the elemental sources in the database can provide a good approximation to the actual tsunami source, then a good source estimation is likely. If not, the accuracy of source estimation might be significantly reduced. So, the completeness of the database is important, but it is unlikely to be achieved due to limited knowledge of the range of possible sources. For example, a tsunami might be generated by rupture of an unknown fault, or a submarine landslide could generate a hazardous tsunami, but these are difficult to predict before their occurrence. Large heterogeneity in the slip distribution of mega earthquake is another source of difficulty. In order to overcome these difficulties, a synthetic method with equidistant elementary sources has been proposed and implemented in tsunami warning. An advantage of the method is its flexibility to represent any kind of tsunami source because it does not assume any mechanism of tsunami generation, it estimates just the form of sea-surface at the tsunami occurrence. The method has also the disadvantage of requiring regularization. Such synthetic methods usually estimate tens to hundreds of unknown parameters, and overfitting is likely to occur, which can reduce forecast accuracy. To avoid this spatial and temporal smoothness constraints are often used for regularization. Regularization is essential to avoid overfitting, but it makes estimation smoother. The estimated source will have attenuated peaks and troughs. This can lead to underestimation of tsunami height in the forecast. For application to warning, it is important to minimize such underestimation.

In this study, we propose to utilize Time Reversal Imaging (TRI) as a generator of elemental sources in a database to minimize the amount of underestimation. TRI is based on the reciprocity principle, which means that the same waveforms should be recorded if the location of the source and observation site are exchanged. This principle holds under the linear wave equation. TRI is obtained by time-reversal propagation of an observed waveform from the observation site to the source. It is subdivided into segments based on their similarity of wave field parameters and position. Each segment is utilized as an elemental source in a database. Some segments are needed to accurately represent the source, but others are artefacts. The source is estimated by waveform inversion with L1-norm regularization, so called “lasso”. Lasso performs subset selection in a database and estimation of coefficients of each elemental source in the subset. The amount of regularization is determined by cross validation. Artefacts are unlikely to survive in this regularized inversion. We will discuss the performance of this proposed method in comparison with TRI.

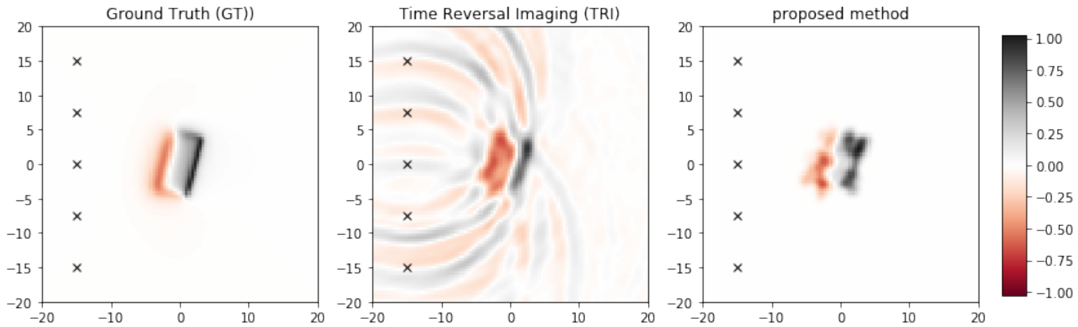

Figure 1. Ground truth of synthetic testing and estimated sources by TRI and proposed TRI-based inversion method. Cross marks indicate observation sites.

Keywords: *Lasso, time reverse imaging, tsunami forecast, waveform inversion*

What if the big flood happens again?

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Abstract: The 1956 flood is considered the largest flood on record for the River Murray. Flooding caused significant property damage in many towns along the river in New South Wales, Victoria and South Australia (SA). The flood occurred due to higher than average rainfall in western Queensland that led to high flows in the Darling River combined with heavy rainfall in the previous months in the Murray-Darling Basin that filled the Murrumbidgee River and the Lachlan River. Flood waters propagated down the Murray and Darling rivers for seven months and peaked in SA towards the end of August. Some areas were flooded up to 100 kilometres from the natural flow of the river. No lives were lost, however the flood was described as "the greatest catastrophe in South Australia's history".

According to information based on articles in the local newspaper, in SA town of Renmark, the event started from May and at its peak the High School, Hospital, 100 homes and 1,250 acres of orchard and vineyard were all flooded. There were serious breaks in the levee banks at Angove's Winery, the No.3 irrigation pump and the Crescent area were flooded. By mid-August, 1,500 people had been evacuated, leaving some 800 men, women and children to battle the rising floodwaters. The people of Renmark never gave up the fight to save the town and it was their determination which helped them to fight for victory. Despite the town itself being saved, the damage to houses, horticultural properties and town facilities was wide spread and the effects of the flood lasted for many years (www.murrayriver.com.au/about-the-murray/1956-murray-river-floods).

The Annual Exceedance Probability (AEP) of the 1956 event, or the likelihood of such flood occurring in any year, was estimated as 0.4% (1 in 250) by the SA Department of Environment, Water and Natural Resources. The event is commonly used for development planning purposes. Approximately one week is required to dynamically simulate this event in existing 2D hydrodynamic models, even on high performance computing infrastructure. While in isolation this is very achievable, this simulation time limits the ability to consider a range of conditions or undertake sensitivity/uncertainty analysis. .

Using a simple conceptual flood inundation model – the TVD (Teng-Vaze-Dutta) model, we were able to simulate the entire flood event in an area surrounding Renmark, at a daily time step for a continuous period of 3 years at a 10-m grid resolution (Figure 1 shows some modelling results). The model was calibrated using remote sensing derived water maps and the results were validated against historical record and observed water levels. The model can be used to explore the impact of the DEM resolution, levee breach and antecedent soil moisture conditions. The results of the modelling were overlaid with the ESRI base map and visualised using video clips generated using python. The modelling can help answer questions such as: what really happened? when did the flood water spread to the town and when did it recede? how deep was the flood water and what was the distribution? how would the inundation extent change with different antecedent conditions or hydrograph shape? and more importantly, are we well prepared if it happens again?

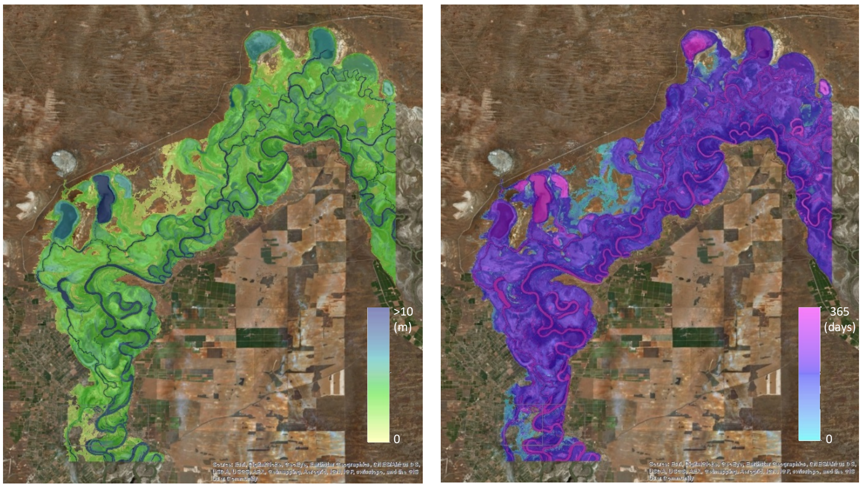

Figure 1. The modelled maximum water depth (left) and number of flooding days (right) in 1956-57 water year for the modelling area near Renmark, SA.

Keywords: *Flood inundation modelling, historical flood event, simple conceptual model*

INVITED PAPER

EXTENDED ABSTRACT ONLY

Capturing surface water dynamics using Landsat and Sentinel-2 satellite data

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Abstract: The mapping of spatial inundation patterns during flood events is important for environmental management and disaster monitoring. Remote sensing technologies provide an affordable means of capturing flood extent with reasonable spatial and temporal coverage for flood monitoring. Landsat and MODIS data are commonly used for producing flood inundation maps since they can cover large remote regions, are readily available (with images from Landsat and MODIS since the 1980s and 2000 respectively) and easy to process. Hydrodynamic modelling tools are widely used for floodplain inundation modelling to a high accuracy, but they are resource intensive, making them impractical to use for large catchments. Remote sensing products are useful and to some extent necessary for both calibrating and validating hydrodynamic and hydrological floodplain inundation models, as well as extending the coverage, although the availability of cloud-free scenes is often limited during flood events. The higher spatial resolution of the Landsat data (30m pixel size) makes it ideal for many flood mapping applications, however its temporal frequency (16 days) is not always suitable for short duration flood events. The first European Space Agency's Sentinel-2 sensor was launched in 2015, providing a spatial resolution of 10-20m, with a temporal frequency of every five days for Australia, increasing the chances of obtaining cloud-free imagery at a spatial resolution similar to Landsat. This increases the capability of calibrating hydrodynamic models at a higher spatial and temporal resolution. A comparison of the Landsat and Sentinel-2 inundation maps was performed for a recent large flood event in the Cooper Basin in central Australia in 2018. Both the Landsat and Sentinel-2 data were converted to images of surface water extent using the modified Normalized Difference Water Index. The number of observations of inundation during April and May 2018 is shown for a subset of the Cooper Basin in Figure 1a and Figure 1b for Landsat and Sentinel-2 respectively. There were up to five cloud-free observations from the Landsat data and 11 from Sentinel-2. The inundation extent for Lake Yamma Yamma (whose extent is outlined in the orange box in Figure 1a) was compared for Landsat and Sentinel-2 from September 2017 to July 2018 (Figure 1c). The results show the extents from Landsat and Sentinel-2 are very similar (with a maximum difference of 1% for the three common acquisition days). The number of cloud-free observations for this period is 18 for Landsat and 56 for Sentinel-2. This analysis demonstrates the benefit of combining the two sensors to better capture the dynamics of flood inundation.

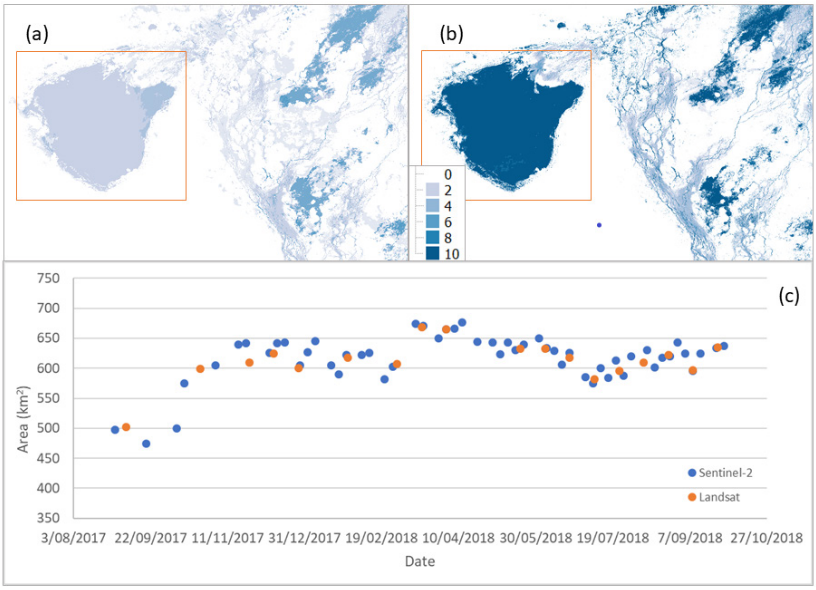

Figure 1. Number of water observations during April-May 2018 for a section of the Cooper Basin (with Lake Yamma Yamma extent outlined in the orange box) for (a) Landsat and (b) Sentinel-2, (c) comparison of surface water extent for the lake during the 2018 flood.

Keywords: *Flood inundation modelling, remote sensing, Landsat, Sentinel-2*

Urban flood modelling and planning system (UFMPS)

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Abstract: There is a great need for tools to assist with complexities associated with input and output data unique to urban flood modelling. For example, it is common for stormwater asset data to be of varying levels of quality. Datasets often include many connectivity issues, unknown invert levels and wrong pipe sizes. Data errors such as these require a large amount of manual labour to rectify before they can be used as stormwater pipe network inputs for urban flood models. In addition to model input issues, the release of the ARR2016 guideline has introduced additional challenges by increasing the number of simulations required for urban flood modelling by up to a factor ten. As such, the adoption of ARR2016 requires additional work in model build, model quality control and model result processing. These challenges have triggered the need to develop a system to improve efficiency and accuracy for urban flood modelling and planning. In this paper, we discuss an urban flood modelling and planning system that automates and manages most of the challenging processes involved in urban flood modelling.

The system encompasses the whole life of urban flood modelling and planning, from model build to the delivery of flood maps and stormwater drainage AutoCAD drawings. The system's main functions include:

- **The model builder:** constructs models with an optimised model structure and naming convention. This allows the system to trace relevant model and result files quickly, and to perform model pre- and post-processing with the minimum user input required.
- **The stormwater pipe network rationalisation tool**: uses a database structure and algorithms to rationalise raw data to comply with the stormwater drainage design criteria specific to network connectivity, minimum pipe grades, maximum pipe grades, and pipe cover.
- **The quality assurer element:** inspects all 1D results to identify instability issues based on desired stability factors. It records any unstable pipes or pits in GIS format for ease of tracking. It also summarises large numbers of simulation log files to assist the identification of models that have been prematurely interrupted or were unstable.
- **The pipe planner**: sizes the pipes based on flows measured from targeted 1D/2D model simulations.
- Other functions of the system include model pre- and post-processing for ARR2016 and ARR1987, a 12d drainage model builder to check interference between the stormwater network and other underground services, an AutoCAD drawings builder to automate the output of 1D hydraulic modelling results in design drawing format and a high resolution flood animation generator linked to Google Earth.

The system is able to build a 1D and 2D coupled TUFLOW flood model, 1D Mike Urban and 12d drainage models with a rationalised stormwater pipe network within 30 minutes for an urban catchment of 1 square kilometre. Without the system, it may take 2 to 3 weeks to rationalise the pipe network for the same dataset. The system can also convert 1D stormwater networks between different flood and drainage models, to perform hydraulic modelling cross checks between different models. The system will be extended to support other models like ANUGA in the future.

The system promotes a framework for consistent model structure and naming convention. As an outcome of this work it is recommended that nationwide protocols should be made for flood modelling and stormwater asset data management. This will make flood and drainage modelling consistent nationally and potentially significantly improve modelling productivity and quality within the broader industry.

Keywords: *Urban flood modelling, stormwater pipe network, ARR2016, efficiency, quality*

INVITED PAPER

EXTENDED ABSTRACT ONLY

Impacts of climate change and human activities on water resources in the transboundary rivers of Central Asia

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Abstract: Central Asia is one of the most complex regions in the world, which is criss-crossed with transboundary rivers shared by several countries. Based on the analysis of the characteristics of temperature and precipitation changes in Central Asia over the past half century, this paper explores the impact of climate change and human activities on the hydrological and water resources of transboundary rivers in Central Asia. The results show that in the past half century, the average temperature in the Tienshan Mountains experienced "sharp" increases in 1998, with the average temperature 1.0 °C higher than that during 1960-1998. The increase in temperatures has reduced the snowfall/rainfall fraction in mountainous areas and aggravated glacier and snow melt, leading to a continuation of glacier and snow cover shrinkage in the Tienshan Mountains in Central Asia. These changes led to the total water storage decreased and influenced the hydrological processes. Nearly all of the rivers in Central Asia originate in the surrounding mountains recharged by meltwater and rainfall. Glacier losses and snow cover shrinkage will further add a new level of complexity of hydrological processes under the context of climate change. Overall, hydrological processes have become more complicated (Figure 1). For example, the runoff of the Naryn River, the largest headwater of the Syrdarya, has increased by 16.5% during 1989-2015 compared to 1933-1988 with glaciers shrinking from 1210 km^2 in the 1970s to 926 km^2 in the mid-2000s. Climate change not only caused changes in water recharge characteristics and runoff magnitudes, but also resulted in changes in intra-annual streamflow patterns. The maximum runoff peaks of snowmelt-dominated rivers occurred earlier in the year, and the glaciermelt dominated rivers generally showed strengthened flood peaks from June to September.

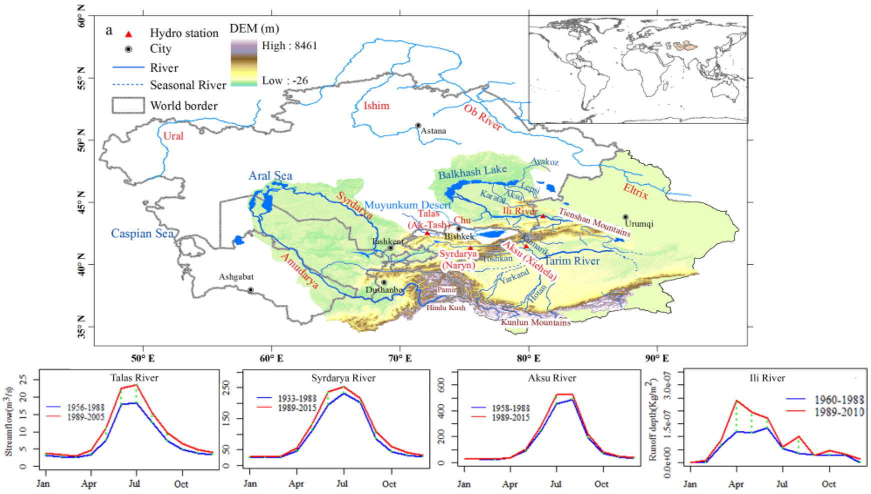

Figure 1. Geographical locations of main transboundary rivers in Central Asia

The influence of human activities on the water resources of transboundary rivers in Central Asia is mainly represented by water resource allocation and over-exploitation. A detailed analysis of the spatial distribution of water and agricultural land in the Aral Sea Basin reveals a serious spatial mismatch. Kyrgyzstan and Tajikistan produce about 70% of the water resources in the entire Aral Sea Basin. However, most of those countries' territory is mountains with very little arable land, accounting for only 14% of the basin's agricultural land. In contrast, Kazakhstan, Turkmenistan and Uzbekistan generate only 20% of the water resources, but the arable land area is as high as 86%. At the same time, there are serious mismatches between water-producing areas and water-consuming areas. Besides, extensive reclamation and expansion of arable land have further exacerbated the water crisis and increased the ecological catastrophe caused by lack of water. The spatial mismatch between water and soil resources and the large-scale development of human water and soil resources have aggravated the water and water crisis in the basin, which is the main cause of cross-border river water conflicts and Aral Sea ecological disasters in Central Asia.

Keywords: *Transboundary rivers, glacier shrinkage, runoff, water conflicts, Central Asia*

Global catchments classification based on machine learning for hydrological signature interpretation

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Abstract: Hydrological predictions in ungauged catchments is a big issue for hydrologists in the last hydrological decade. One remained key question is how to define the hydrological similarity to accurate find the donor catchment(s) for regionalization process. Understanding dominant controls of meaningful information transfer from gauged to ungauged catchments is particularly valuable for this question. Global large-sample analysis may give useful insights on how these runoff signatures behaviors look like based on the significant catchment attributes classification.

This study explores different runoff signature behaviors based on catchment attribute classifications in the case of catchments across global catchment dataset. This global dataset with over 20000 catchments includes both catchment attributes collecting from Google Earth Engine and daily runoff series from public dataset of different countries. Then Clustering methods on the input consisting of topography, soil, geology, land cover and climate attributes are employed to identify similar groups of catchments. The catchment attributes are screened out based on filter algorithms for the clustering in advance. Hydrological attributes such as 95% flow percentile (low flows), mean daily discharge (medium flows), and 5% flow percentile (high flows) and Hydrograph characteristics such as recession curve index are analyzed in each clustering group. If the runoff signatures show similarity in the same cluster group, then the clustering strategies are accepted, otherwise the whole clustering procedures are repeated with different strategies. The final clustering results are presented in Budyko curve to check whether the annual water balance behavior is significant in each clustering group. These behaviors are combined with the common hydrological signatures in each clustering group to better interpret hydrological signature regional distribution globally.

We find that understanding hydrological similarity and catchment classification are particularly important when predicting runoff in ungauged catchments. Since this understanding have implications for donor catchment selection and hydrological regionalization. Different hydrological similarity criterion will be proposed and compared for hydrological regionalization in the further study.

Keywords: *Catchment classification, clustering, large-sample analysis, hydrological regionalization*

Long-term vegetation change and its driving factors in a typical catchment of the Loess Plateau

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Abstract: Vegetation information is critical for understanding terrestrial water and carbon dynamics, and is a key factor for regional environment management under climate change. This study selected a typical arid and semi-arid catchment, in the Loess Plateau, the Zuli River Basin (ZRB) to investigate the long-term vegetation cover change and its driving factors. Different from available Normalized Difference Vegetation Index (NDVI) products that were produced at coarse spatial resolutions and with short temporal ranges, high-resolution (30m) and long-term (31 years) NDVI data was generated in this study by using 30m resolution Landsat dataset analyzed within the Google Earth Engine (GEE), a cloud platform with planetary-scale analysis capabilities. We evaluated the relationships between NDVI and precipitation, runoff coefficient and sediment concentration using cross wavelet, and explored the impact of precipitation on vegetation and the impact of vegetation cover on runoff and sediment before and after the implementation of Grain for Green Project (GGP, conservation program designed to mitigate and prevent flooding and soil erosion in China) in different parts of ZRB in 1956-2016. Our results show that there was an increasing trend in average maximum annual NDVI across the ZRB during 1987-2016 and a significantly ($p < 0.05$) increased trend in most areas. The vegetation cover increases in upstream Chankou and upstream Huining (two representative catchments within the ZRB) was higher than that in the middle stream and downstream, but with a smaller increase rate. Widespread increase in vegetation mostly occurred after GPP because the area with significant increase from 1987-2016was higher than the increased area in 1987-1999. The precipitation had significant correlation ($p < 0.05$) with NDVI series across the ZRB except for the upstream Chankou where human activities played a major role. The relationship between NDVI and the runoff coefficient, sediment concentration was significantly negative ($p < 0.05$), which indicates that the vegetation cover is an important reason for reduction of runoff coefficient and sediment concentration. Meanwhile, the human activities also played a positive role on both restoration of vegetation and reduction of runoff coefficient and sediment concentration across the ZRB.

Keywords: *Vegetation cover, Normalized Difference Vegetation Index, Grain for Green Project, precipitation, human activities*

The spatio-temporal NDVI analysis for two different Australian catchments

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Abstract: Contrasts in insolation lead to the development of aspect-controlled ecosystems characterized by heterogeneity in vegetation type and density in semi-arid ecosystems. The aspect-controlled solar radiation creates variation in the type and amount of vegetation across the two opposite facings of the hillslopes. In the Southern Hemisphere (SH), the north-facing slopes (NFS) have an abundance of paleotropical xeric biota, whereas the south-facing slopes (SFS) have higher densities of mesic temperate species. The reverse patterns are mostly observed in the Northern Hemisphere (NH). In the SH, SFS are dominated by the evergreen sclerophyllous woodland, while open scrub vegetation with spiny shrubs, sub-shrubs, and small trees exist on the NFS. This general vegetation pattern creates differences in erosion control and resistance on different slopes, and thus the underlying landscapes evolve differently. Although many previous studies have focused on aspect-controlled vegetation growth in the NH, there have been limited studies in the SH, especially in Australia.

Remote sensing provides one of the best options to capture the long-term biomass changes over the large spatial and temporal coverage. The normalized difference vegetation index (NDVI) is based on the relationship between the reflectance of the red and near-infrared bands of multispectral sensors, and it can be used due to its computational simplicity and easy accessibility. In this study, we considered two catchments, Mount Wilson, South Australia and Risdon Hills in Tasmania to study the long-term spatial and temporal variation in NDVI at these catchments. Both sites are unaffected or minimally affected from anthropogenic activities upon visual inspection through Google Earth™, in addition to reviewing both sites from the literature. We also explored how the precipitation and potential evapotranspiration patterns at these sites affect the vegetation growth during the year.

In this study, we extracted NDVI values derived from Landsat 5, 7, and 8 (obtained from Google Earth Engine) for a 18-year period (2000-2017) for both catchments. Thereafter, we used 30-m SRTM DEM to calculate the aspect and slope datasets for two locations. With the aspect data classified, the vegetation index NDVI is computed for each slope, NSF and SFS. We compared and contrasted the inter-annual variability in NDVI at the two sites to capture the temporal variation in NDVI. We have also introduced $NDVI_{diff}$ as the difference between NDVI at NFS to SFS, where $NDVI_{diff} > 0$ states that NDVI is higher on NFS than SFS and vice-versa. The spatial NDVI is extracted for the summer and winter months, November and June, respectively, to see the seasonal NDVI at each catchment.

The results show that the Mount Wilson site (~35°S) has higher NDVI values than the Risdon Hill site throughout the year though receiving similar annual precipitation. It is observed that the Mount Wilson site shows approximately similar NDVI on NFS and SFS in the austral summer period. However, in the winter season when seasonal total precipitation exceeds total PET demand, the NDVI on NFS is comparatively higher than on SFS, which is attributed to differences in vegetation phenology on opposing hillslopes and relatively more incoming solar radiation on NFS than SFS. On the other hand, the site at Risdon Hills (~42°S) has relatively lower range of NDVI at both NFS and SFS, and NDVI at NFS and SFS does not vary noticeably. Further, the spatial NDVI patterns at both locations also illustrate similar behaviour, following the temporal patterns at both locations.

Keywords: *NDVI, remote sensing, aspect, insolation*

A high-resolution paleo streamflow record for Monsoon Asia with surrogate streamflow data

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Abstract: Streamflow reconstruction is the study of rivers in the past, reconstructing their discharges using climate proxies such as tree-rings. Recently, the first large-scale reconstruction for 66 river basins in Monsoon Asia [1] has provided insights into the spatial-temporal variability of streamflow throughout the region over the past eight centuries. Yet, the spatial analysis was hampered by the lack of (or inaccessibility to) data in many rivers. On the other hand, advances in hydrologic modelling, with both physics-based and data-driven models, have produced regional and global streamflow estimates that match well with observations. These datasets have high resolution and large spatial coverage, but they typically span only a few decades, insufficient to capture long-term hydrologic variability. Here, we are interested in leveraging the spatial coverage of simulated streamflow and the time span of reconstructed streamflow. Can simulated streamflow be a surrogate for instrument data in streamflow reconstruction? If so, what insights can we gain from such a hybrid dataset?

To address these questions, we develop a high-resolution paleo streamflow record for the Monsoon Asia region based on FLO1K, a global streamflow dataset produced by a data-driven hydrological model at 1-km resolution [2]. We first vectorize FLO1K and remove small river reaches (mean annual flow < 50 m^3/s); this step reduces the number of data points while maintaining the integrity of the river network. We then extend the vectorized FLO1K back to 1200 CE using the modelling approach presented in [1]. We use the Monsoon Asia Drought Atlas (MADA) [3] as the paleoclimate proxy; the inclusion of MADA grid point is guided by the KWF climate classification system [4]. The relationship between MADA and streamflow is identified using a linear dynamical system model [5], which accounts for both catchment memory and catchment state (wet/dry), thus is better at capturing prolonged droughts and pluvials than conventional linear regression.

Results show that reconstruction skills with FLO1K and observed streamflow are similar, which implies that FLO1K can indeed be a surrogate for streamflow data. The FLO1K reconstruction also highlights regions with potential for skillful reconstruction, such as southeastern China, thus guiding future reconstruction efforts. More importantly, the surrogate reconstruction provides a clearer picture of past droughts and pluvials than previous works, with more detailed hydrological footprints of megadroughts in the last millennium. It enables spatial analyses that are otherwise difficult with the limited gauge network and reveals several regional variation patterns. We identify a gradient of ENSO influence on streamflow: influence is strongest in Southeast Asia and decreases westward towards India and northward towards China. Overall, the findings presented advance understanding of regional hydrologic variability and can help improve water resource management in many river basins.

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Keywords: *Streamflow reconstruction, Monsoon Asia, streamflow variability, high-resolution*

Irrigation expansion, groundwater declines: hydrological drivers in northwest Bangladesh

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Abstract: The northwest region in Bangladesh has the largest areas of irrigated agriculture and supplies about 35% of all dry season rice (Boro rice) and more than 60% of the wheat and maize to the nation. In some parts, declining groundwater levels (GWL) resulted in the need to deepen wells, with the associated higher cost of pumping and impact on yields. This is of great concern for the sustainability of dry season irrigation, which is vital to the country's recent near-attainment of rice grain food security. There is also evidence of declining rainfall and (to a lesser extent) streamflow. Actual evapotranspiration (ET_a) estimates were obtained using two methods that capture changes in irrigated agriculture. The first method estimated monthly ET_a at 500 m spatial resolution from 2000 to 2015 using the CMRSET (Csiro Modis ReScaled EvapoTranspiration) algorithm. Monthly ET_a is estimated by scaling ET_p via a crop factor (K_c), which is obtained from two vegetation indices from the MODIS nadir BRDF-adjusted reflectance (NBAR) product. The second method reconstructed a monthly composite K_c from 1985 to 2015 using: (i) district-wise area crop statistics data (for over 15 crop types) collected yearly and (ii) inferred crop sequences, and then scaled by ET_p. Both methods yielded very similar results for the 16 districts in northwest Bangladesh, with correlation coefficients between 0.75 and 0.89. The maximum difference between the monthly averages was only of 5.4%. The seasonal non-parametric Mann-Kendall test and the Sen-slope method were used to investigate trends in observed and modelled data, including: rainfall, GWL and ET_a. Results at the district level showed confounding results, with districts to the north showing decreasing trends in rainfall, mixed (some slightly increasing, some slightly decreasing) trends in ET_a, and slightly (but significant) declining GWL. On the other hand, districts to the south showed slightly decreased rainfall, mixed trends in ET_a and significant declines in GWL (Fig. 1 for ET_a and GWL trends). To elucidate the trends, a water balance model was implemented for the 16 districts in northwest Bangladesh and aggregated to assess changes over the long-term and seasonally (annual, dry season and wet season). This was performed for three evaluation periods; 1985–1989, 1998–2002 and 2011–2015. These periods were chosen to assess long-term changes associated with the rapid expansion of irrigated areas and groundwater decline. Rainfall and ET_a dominated the water balance. ET_a is similar (around 1100 mm) across districts. Although rainfall declined from 1985 to 2015, ET_a generally remained about the same. Annually, runoff is approximately equal to the difference in rainfall and ET_a (with some recharge to groundwater) and varies from about 300 mm to about 1900 mm and is mostly determined by the variation in rain amongst the districts. Because of the decline in rainfall, runoff declined in all districts from 1985 to 2015. From the water balance, it is inferred that both the groundwater extraction (by pumping for irrigation and capillary rise to supply roots) and the groundwater recharge reduced from 1998–2002 to 2011–2015, and with deeper groundwater in later years, much of the irrigation water supply is by soil water storage rather than by groundwater, particularly in districts to the south.The water balance model pointed to other factors aside from crop expansion that may have contributed to the groundwater decline such as reduced rainfall and recharge. To tackle declining groundwater levels, a single policy or management change such as restricting groundwater extraction for irrigation may alone be inadequate and have deleterious impacts on people's livelihoods.

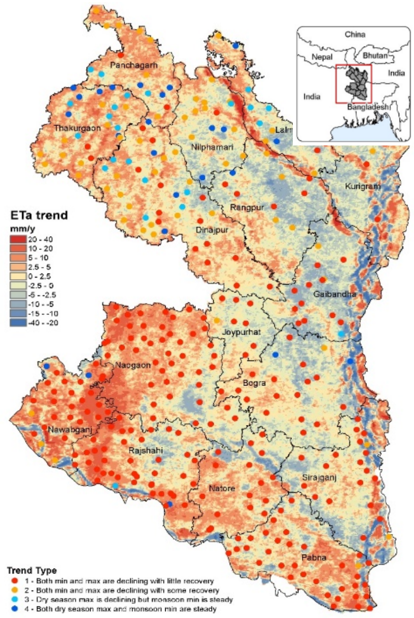

Figure 1. Spatial ET_a trends and GWL trends (coloured dots) indicating type of trend according to GWL behavior by season

Keywords: *Remote sensing, evapotranspiration, crop factor, groundwater extraction, Boro rice, Bangladesh*

Time series mapping of cropped areas and water use patterns in the Indus Basin Pakistan

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Abstract: The Indus Basin Irrigation System (IBIS, ~140,000 km^2) provides food for about 207 million people in Pakistan. The semi-arid climate and nearly-fully allocated surface and groundwater water resources represent a continuous management challenge. The construction of hydraulic infrastructure that regulates and conveys available water has played a pivotal role to increase the efficiency of existing irrigation systems. Diagnosing the improvements in irrigation performance by implementing such dedicated infrastructure has been hampered by lack of enough water supply and use data. Multi-temporal remote sensing data can potentially provide crop types, extent and associated evapotranspiration, which can be used to assess irrigation performance in large irrigation systems such as the IBIS. Google Earth Engine enabled the processing of the archive of the Landsat (30 m horizontal resolution, 16-day revisit period) and MODIS (250–500 m resolution, daily revisit period) missions' multi-spectral data for the IBIS. Two vegetation indices were processed from the spectral data and downloaded: The Enhanced Vegetation Index (EVI,) and the Global Vegetation Moisture Index (GVMI). EVI is related to evapotranspiration (ET_a) through its relationship with leaf area index, whereas GVMI is sensitive to vegetation water content at high EVI values and to surface water and wet soil at low EVI values. Monthly time-series of EVI and GVMI at Landsat 30 m resolution were used through a Machine Learning semi-supervised classification approach to map main seasonal crop types across a large irrigation canal (the Nara canal, irrigated area of ~8,100 km^2) command in the IBIS, yearly from 2000 to 2017. The accuracy of the obtained maps was assessed against crop area statistics obtained from agricultural surveys (Fig. 1). In addition, 10-daily actual evapotranspiration (ET_a) estimates were obtained at 500 m spatial resolution from 2000 to 2017 using the CMRSET (Csiro Modis ReScaled EvapoTranspiration) algorithm. ET_a is estimated by scaling potential evapotranspiration (ET_p) via a crop factor (K_c), which is obtained from the two vegetation indices. Further, ET_a was resampled monthly at Landsat 30 m resolution and associated to prevalent crop types. The 500 m ET_a estimates were compared to published monthly remote sensing ET_a products that are available for a limited number of years, showing reasonable accuracies both in magnitude and timing (Fig. 2). The information rendered by remote sensing can be used to assess the equity, adequacy and reliability of the irrigation systems; and thus, inform decisions to improve outcomes for farmers' livelihoods.

***Keywords**: Remote sensing, evapotranspiration, crop factor, Pakistan, machine learning*

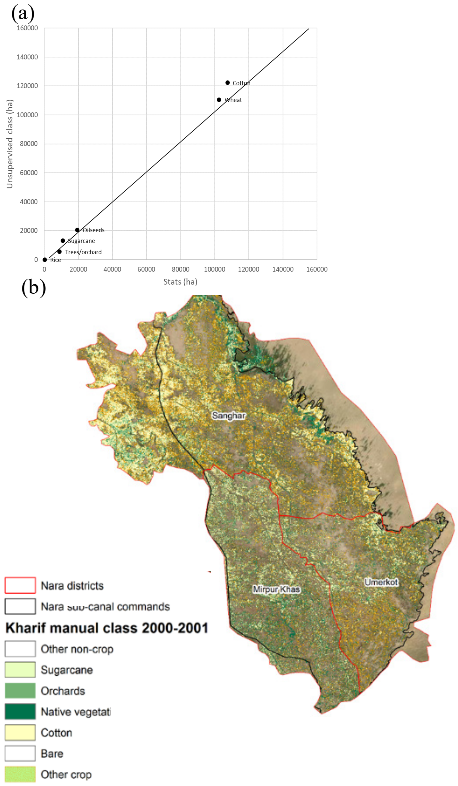

Figure 1. (a) Comparison of remotely-sensed mapped areas and crop survey statistics for the Kharif (wet) season in the Nara canal and (b) Location of main crops mapped

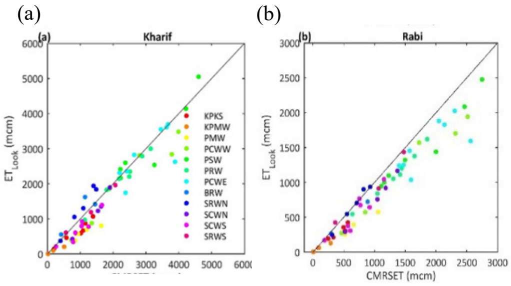

Figure 2. (a) Comparison of remotely-sensed ET_a obtained by CMRSET and ET_{Look} for (a) the wet season and (b) the dry season. Dots indicate different districts and colours indicate different agro-climatic zones

A pixel-based indicator of upland crop waterlogging using remote sensing soil moisture data

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Abstract: The waterlogging hazard is a serious agricultural disaster for upland crops in agricultural cultivation regions of humid climate over the world, such as in South China, South-east Asia and South Asia. Traditional waterlogging monitoring and risk assessment are usually carried out with a limited number of in-situ meteorological-based observations by using certain kinds of hazard evaluation indicators, and the effectiveness could be easily hampered by unsatisfied spatial coverage, high expense, and more importantly, the neglect of soil texture heterogeneity. In this study, we proposed a novel method for quantifying the occurrence threshold of waterlogging at upland croplands based on AMSR-E/AMSR-2 remote sensing soil moisture dataset and constant spatial information of soil texture. The method was applied to the croplands in the middle and lower reaches of the Yangtze and Huaihe Rivers in China. The method used local crop phenology pattern of the “paddy-upland rotation”, mainly the soil water demand discrepancies of different crops in different seasons within the study area. Then we conducted pixel by pixel analysis to extract four different soil moisture values, namely $Rht_{0.2}$, $Rht_{0.4}$, $Rht_{0.6}$, and $Rht_{0.8}$, from the soil moisture temporal dynamics during the paddy rice growth season. The values were taken as waterlogging thresholds to simulate waterlogging disasters. The simulations were validated against historical waterlogging records from 14 counties located in the study area. Validation showed that $Rht_{0.6}$ achieved the best performance in capturing the actual waterlogging days, with 7 of the 14 counties having monitoring accuracies higher than 70%. In the subsequent step, a multiple linear regression model was developed to express $Thr_{0.6}$ as a function of soil texture parameters (i.e. soil sandy fraction and soil clay fraction), which results in a determination coefficient (R^2) of 0.77. This suggests the feasibility of a remote-sensing-pixel-based indicator for modelling the soil moisture threshold to evaluate the occurrence of waterlogging at upland croplands (e.g., winter wheat and oilseed rape). The indicator is advantageous for considering the heterogeneous underlying soil characteristics of different pixels, and also at its independency of a complicated and expensive network of in-situ meteorological-based observations. Our following studies will take more environmental factors into account apart from soil texture parameters, in order to further enhance the indicator for better estimation of the waterlogging threshold. Also, this pixel-based indicator will be applied for the development of an integral framework for monitoring upland crop waterlogging in a near-real-time manner at regional scale, with remote sensing soil moisture datasets at finer resolutions.

Keywords: *Soil moisture, passive microwave remote sensing, AMSR, waterlogging disaster, upland crop*

Estimating coupled high resolution global evapotranspiration and gross primary production using the Google Earth Engine

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Abstract: We are living in a rapidly changing world, with geophysical datasets being created at fast increasing rates. How to better use these datasets for understanding hydrological processes in various climate, vegetation and anthropogenic-influenced regimes has become a challenge and an opportunity. This study uses the latest version of Penman-Monteith-Leuning model (PML-V2) to estimate 500 m and 8-day resolution global evapotranspiration (ET) and gross primary production (GPP) in 2002-2017 by using the Google Earth Engine (GEE), a planetary-scale platform for Earth science data and analysis, which takes MODIS data (leaf area index, albedo, and emissivity) together with GLDAS meteorological forcing data as model inputs. PML-V2 uses a water-carbon coupled canopy conductance model to estimate transpiration and GPP.

PML-V2 was well calibrated and validated against 8-day measurements at 95 widely-distributed flux towers and 10 plant functional types across globe, indicated by Root Mean Square Error (RMSE) and Bias being 0.69 mm d^{-1} and -1.4% for ET respectively, and being 2.04 gC m^{-2} d^{-1} and 3.04% for GPP. Over these sites, the PML-V2 estimates were noticeably better than most GPP and ET products that are widely used across global water and carbon communities. The well parameterised PML-V2 in the 10 plant functional types was then used to estimate global ET and GPP across each 500 m resolution grid cell. The PML-V2 estimates show that global ET both GPP significantly ($p < 0.001$) increased over the last 15 years. The PML-V2 estimates clearly detects large-scale land cover change impacts on ET and GPP. For instance, PML-V2 estimates show that with large-scale urbanisation in eastern and southeastern China both ET and GPP have noticeably decreased over the urbanisation areas in the last 15 years. The PML-V2 also detects decrease in ET and GPP during droughts in southeastern Australia and California, and but finds that climate change has only marginal impacts on ET and GPP in the regions with large scale groundwater irrigations, such as North China Plain. PML-V2 estimates also show that ET and GPP have significantly increased ($p < 0.001$) in the areas with strong greening, i.e. increase in leaf area index. It highlights that the Grain-for-Green Project in the Loess Plateau that was launched in 1999 as an ambitious conservation program designed to mitigate and prevent flooding and soil erosion strongly varied hydrological processes, with increase in ET and GPP, but decrease in surface water availability and catchment streamflow.

In summary, the Google Earth Engine is a great platform to execute PML-V2 for estimating up-to-date 500 m and 8-day resolution ET and GPP products. This allows researchers to have comprehensive analysis on land cover change impacts on water and carbon fluxes from patch to global scales. This is the ongoing study, and we are trying to further improve PML-V2 accuracy and reduce its uncertainty in forcing data, model structure and parameterisation schemes.

Keywords: *Evapotranspiration, gross primary production, PML-V2 modelling, coupled estimates, globe, the Google Earth Engine*

Changes of Bowen Ratio of alpine grasslands in the Three-Rivers Headwater Region of the Qinghai–Tibet Plateau in 2000-2018

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Abstract: Biophysical effects of land use and cover changes is an important topic in global change researches. On the Qinghai–Tibet Plateau, over-grazing induced alpine grassland degradation has been changing energy balance between latent heat and sensible heat, so-called Bowen ratio defined as the ratio of sensible to latent heat. In this study, we used two datasets to analyze the spatial-temporal variability in Bowen ratio and tried to discover the contribution of vegetation in biophysical effect in the Three-Rivers Headwater Region (TRHR) in 2000-2018. The latent heat or evapotranspiration (ET) were derived from both the MODIS product of MOD16A2 V006 and an air-relative-humidity-based two-source (ARTS) model [Yan *et al*., 2012]. Both the data were validated against the observations of eight years from 2003 to 2010 on the eddy covariance tower at the Haibei station, Qinghai province. The results showed that the estimated latent heat significantly correlated with the observations with the correlation coefficients (R^2) of 0.61 and 0.71 ($p < 0.01$). According to the mean latent weighted by the R^2 from the validations for the two models, the averaged Bowen Ratio (β) was 2.60 for the grasslands of the whole study area, which meant that the about 28% of net radiation were latent heat used for evapotranspiration, and 72% for sensible heat during the 19-year period. For the headwater regions of Yangtze River, Yellow River, and Lancang River, the β values were 2.57, 2.17, and 2.35, respectively, that is, Yellow River transferred more heat for evapotranspiration, while Yangtze River made air warmer, which would attribute to their different attitudes and grassland coverage. According to land use and cover data, the β increased from 2.61 to 3.17 along the coverage from higher to lower fraction in whole region and same in each headwater. By compare the β of three coverage grassland between the two periods of 2000-2010 and 2010-2018, we found that the β increased by 16.70%, 20.45% and 3.21% along with the decreasing grassland coverage from the higher to lower, from the higher to middle, and from the middle to lower fraction. In the period from 2000 to 2018, the βshowed an insignificant decreasing trend with a slope of 0.40 ($R^2 = 0.16$, $p = 0.09$), meanwhile its climate was significantly warming by a rate of 0.86 °C per decade ($R^2 = 0.61$, $p < 0.001$) and insignificant wetting by a rate of 24.1 mm per decade ($R^2 = 0.07$, $p = 0.24$). According to normalized difference vegetation index (NDVI) from MODIS product (MOD09Q1), its vegetation was greening by a rate of 0.06% ($R^2 = 0.18$, $p = 0.06$) for the whole region. According to the R^2 of the multiple linear regression between the βand the environmental factors in the study period, the annual mean temperature, annual precipitation and NDVI of grassland together could explain 34% (R2 = 0.34, p = 0.091), while albedo and relative humidity can explain extra 19% (R2 = 0.53, p = 0.057) of the temporal variability in Bowen ratio in the 19 years. This study firstly analyzed biophysical effect of alpine grassland through a synthesized data from two models aimed to decreasing uncertainties and discover its driving factors from climate and vegetation changes. However, considering the freeze-thaw over the Qinghai-Tibet Plateau, the mechanism of energy balance is more complex and more field observations are needed in the future studies.

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Keywords: *Sensible heat, latent heat, Bowen Ratio, alpine grassland, MOD16, ARTS*

Simulated temperature and precipitation changes on the Tibetan plateau by state-of-the-art climate models

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Abstract: The Tibetan Plateau (TP) is "the third pole" because of its vast fresh water reservoirs and ice fields. The TP plays an important role in the evolution of regional climate and global atmospheric circulation, with significant variations of temperature and precipitation. Warming in the TP is remarkably faster as compared with the northern hemisphere (0.38°C per decade) and worldwide(0.32°C per decade), and the precipitation in TP is increasing in recent decades. Because the TP is sensitive and fragile to global change, an understanding of future climate change is vital for the sustainable development of this region. Climate system model is the most important tool for predicting climate change. The more accurate simulating in the past, the more credible results in the future. The output of state-of-the-art global climate models (the 6th phase of Coupled Model Inter-comparison, CMIP6) is being released to climate community.

We examine the performance of 10 models participating in CMIP6 over the TP by comparing their outputs with outputs of CMIP5 and ground observations of surface air temperature and precipitation for the period 1986-2005. The results show that CMIP6 models underestimate annual temperatures, with a minor negative bias compared with CMIP5 in the center region of the TP and have a larger negative bias in the west . CMIP6 models can reasonablely capture the climatological spatial patterns of annual temperatures, and perform better in reproducing annual precipitation than CMIP5. CMIP6 models can capture the climatological spatial pattern of annual precipitation that mainly feature a northwest-southeast increase. CMIP6 models still have a slight wet bias in precipitation, especially in the southern region, which is smaller than that of CMIP5, particularly in the central region. Our results suggest that the ability of CMIP6 models to simulate surface temperature and precipitation has improved when compared with CMIP5. Overall, the models in CMIP6 show limited capacity in simulating precipitation. The simulated precipitation results in the TP should be used with caution.

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Keywords: *Climate model, climate changes, the Tibetan plateau*

The effect of in-stream dam development on flood-mitigation in the Fitzroy River, Western Australia

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Abstract: The potential of irrigated agriculture in the Fitzroy Valley of Western Australia has been recognised since the 1950's. Early trials of rice and safflower soon followed and irrigation development was initiated in the Fitzroy Valley with assistance from the Western Australia Department of Agriculture. However, these and repeated subsequent attempts by various government and privately owned organisations, failed, in large part due to infrastructure damage from floods. In this regard, the construction of large in-stream dams has been suggested as a means of supplying irrigation water and reducing flooding in the Fitzroy Valley to such an extant that irrigated agriculture becomes more viable.

However, large in-stream dams in the Fitzroy River will drastically change the hydrology of the river system with probable large effects on both aquatic and floodplain ecosystems. Additionally, construction of large in-stream dams ignores cultural values/rights of many Traditional Owners and non-indigenous people of the Fitzroy Valley. For these reasons the Western Australian government has a no large dams policy in the Fitzroy catchment.

Recently the CSIRO completed the Northern Australia Water Resource Assessment (NAWRA), a large multi-disciplinary water and agricultural resource assessment. As a part of that study, a river model of the Fitzroy was built allowing the assessment of various development scenarios. NAWRA did not include any assessment of large in-stream dams, however. Although no dams are likely to be built in the Fitzroy Valley, the data acquired and models developed as a part of NAWRA offer a unique opportunity to test the risks and effects of two large, in-stream dams in the Fitzroy catchment, designed and operated specifically for flood mitigation.

Keywords: *River system model, large dams, Fitzroy River WA, Flood peak, Flood extent*

Development of an interactive river system model based on a web application

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Abstract: Web applications are growing in popularity as they facilitate access to numerical models, reproducibility of scientific research and enable users to interact with data. Historically access to calibrated river system models has been limited to state and territory hydrologists and selected consultants. Other stakeholders are generally unable to access river system models due to a lack of technical knowledge, computational and software license restrictions as well as a general reluctance by government to make such tools readily available.

We present a web-based river system model named "Northern Australia Water Resource Assessment–river" (NAWRA-river, https://nawra-river.shinyapps.io/river/), which aims to make the river systems models developed as part of the Northern Australia Water Resource Assessment (NAWRA) readily accessible to all stakeholders, and in doing so provide transparency in the river system modelling undertaken as part of the Assessment. The river system modelling in NAWRA-river offers a comprehensive and interactive integrated evaluation of the feasibility of water resource development and the potential impacts to ecologically sensitive flow regimes. NAWRA-river integrates the following models in a single web-based application: i) AWRA-R model – a semi-distributed 'node-link' model that estimates ungauged inflows, routing transformation, transmission losses and other processes at the node scale, ii) irrigation model – this is a component of the AWRA-R system, although modified for northern Austalian applications. The model has functionality for on-farm storage of water or direct irrigation from the river. Allocation volumes, pump capacity and pumping characteristics can all be modified to suit desired scenario analysis, iii) dam model – this model simulates the potential impact of dam operations. It controls releases of water by a list of parameters which are user modifyable and provides outputs of reservoir volume and dam spill, iv) eco-hydro model – this calculates the relativance of changes in flow characteristics to each ecological asset, and v) habitat preference model – this model calculates the condition of selected species based upon the flow regimes.

When run, NAWRA-river produces the results of two simulations, Scenario A and Scenario B. Scenario A is considered the baseline simulation and is produced assuming historical climate (1890 to 2015) and current levels of development. Scenario B is the historical climate and a potential future development, as parameterized by the user. The future development may bewater harvesting into large farm-scale ringtanks, major instream dams or a combination of both. Simulation for Scenario B can be customised by changing model parameters on the web interface, such as the volume of water to be extracted annually, location of water extraction, rate of extraction and minimum threshold at which water can be extracted. This modelling framework enables the user to explore the trade-offs of potential water resource development on existing users and the environment.

The web interface was built using R shiny package and it provides many interactive components. A key feature includes a zoomable interactive map of the river system to help users understand the river model spatial structure, where each reach and node is displayed. The web interface also enables the user to underlay spatial datasets such as a flood extent and agricultural versatility on the river system to inform the configuration of their future development scenarios.

Keywords: *River system model, water harvesting model, dam model, eco-hydro model, habitat preference model, web application*

EXTENDED ABSTRACT ONLY

The effect of future hydropower dams on the hydrological regime of African rivers

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Abstract: The world is facing an increasing electricity demand in the next decades. In order to mitigate climate change, the development of hydropower dams is currently the most used strategy to enhance renewable energy sources. At present more than 3,700 large hydropower dams are planned or under construction, most of them in emerging economies in Southeast Asia, South America and Africa. Damming rivers, however, has major implications on river systems, which includes sediment transport, ecological passability and discharge variability. While for existing dams the latter can be calculated from gauging data this is not possible for future dams. For this reason, we used a conceptual model propagating the effects of reservoirs as attenuators on discharge dynamics depending on dam locations and reservoir volumes to quantify the impacts of future hydropower dams.

In our study we focused on African river basins with about 300 new large hydropower dams in near future. We implemented a GIS-based segmented river routing model based on the HydroSHEDS river network, driven by mean monthly discharges from the WaterGAP model as well as dam locations and derived reservoir volumes of future hydropower dams. The model calculates from a given range the reservoirs' most probable specific attenuation on monthly discharges and propagates these effects downstream through the river networks. As a result, variation coefficients and Seasonal Regime Indicators (I_{SR}) were calculated to indicate the effects of changed seasonal discharge variability of each river segment in future compared to the status quo. Values of all river segments in a basin were aggregated to overall basin indicators for easier comparison.

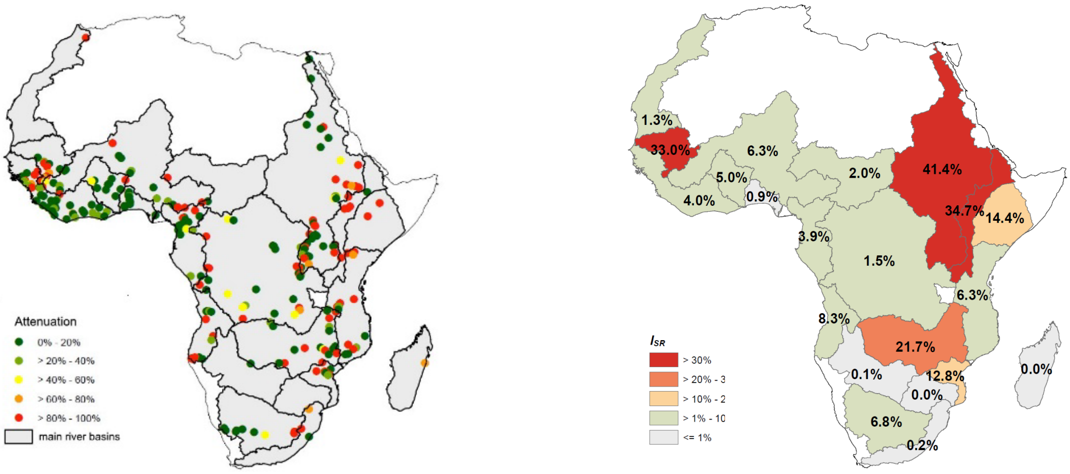

Figure 1. Calculated local attenuation of each future hydropower reservoir on seasonal discharge dynamics (left) and aggregated effects in main African river basins given by the Seasonal Regime Indicator I_{SR} (right).

We found about half of all dams with a local attenuation effect of 20 percent or lower while nearly one third of all dams reach an attenuation effect of more than 80 percent. For most of the main river basins we calculated an overall moderate mean reduction of seasonal discharge dynamics of all river segments by up to 10 percent. The basins of Nile, Senegal, Omo and Zambezi, however, will face a more severe overall decrease from at least 20 percent up to more than 40 percent.

Because we used a generic dam management scheme for this study results may change when we implement a more realistic dam management scheme by optimizing the scheme for electricity production in future.

Keywords: *Hydropower dams, hydrological regime, discharge dynamics*

Evaluating the impact of flood extent assimilation on hydraulic model forecast skill

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Abstract: Accurate flood inundation forecasts have the potential to reduce impacts and minimize socioeconomic losses. Yet, present day global flood forecasting systems only provide streamflow forecasts. The primary reason for this is the dearth of appropriate global elevation data which can meet the accuracy needs of flood inundation modelling. Moreover, uncertainties in input inflows propagated from the precipitation forecasts, further exacerbate the resulting forecast error. Recent studies suggest that the assimilation of independent flood observations can effectively mitigate the inherent uncertainty in hydraulic flood inundation modelling. The increasing number of Earth observation satellites have enhanced the probability of monitoring flood dynamics from space. Synthetic Aperture Radar (SAR) sensors, in particular, have demonstrated potential for flood monitoring due to their time and weather independent imaging skills. SAR-based flood extents have been used for the indirect retrieval of floodplain water levels, which were subsequently used for flood data assimilation. However, more recent studies have recommended the direct assimilation of flood extents, eliminating the need for water level estimation. In this context, earlier studies have struggled with the development of an appropriate cost function to define the innovation at each assimilation time step. This is overcome in this study by developing a novel reliability diagram-based cost function, and the potential of this approach for flood forecasting is demonstrated through a real case study. This cost function is implemented within a particle filter based flood extent assimilation framework, developed using the hydraulic model LISFLOOD-FP, for the 2011 flood event in the Clarence Catchment Australia. A real world scenario was emulated for the open loop model ensemble, with the consideration of uncertainties in inflows, initial conditions, parameters (channel roughness and geometry), and topography. The impact of assimilating flood extents, derived from two post-peak Cosmo-SkyMed SAR images, using the proposed cost function on the forecast skill was evaluated. Contingency maps depicting the differences between the open loop and assimilation runs, from a synthetic experiment in which only inflow errors were considered, show visible reductions in over-prediction (Figure 1). Results indicate that the proposed cost function has the potential to improve the efficiency of flood extent assimilation.

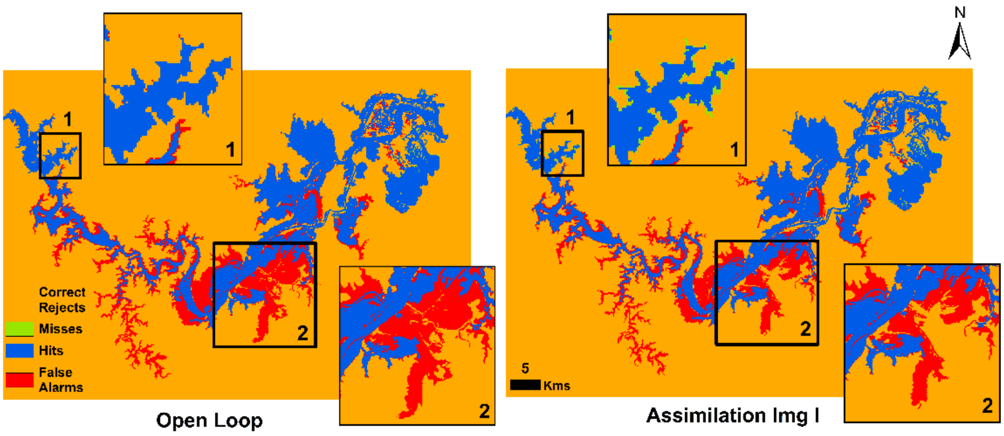

Figure 1. Contingency maps illustrating a comparison between the forecast and true flood extents, for the open loop (no assimilation) and assimilation runs, at the assimilation time step.

Keywords: *Flood inundation modelling, flood extent assimilation, SAR, data assimilation, hydraulic modelling*

Efficient simulation of flood events using machine learning

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Abstract: Flooding is one of the most common and costly natural hazards at global scale. Flood models are important in supporting flood management. Numerical models for flood waves solve hydrodynamic equations to calculate water depths and flows over a specific domain. This is a computationally expensive process, due to the high nonlinearity of the equations involved and the complexity of the surface topography. New modelling approaches based on deep learning algorithms have recently emerged for multiple applications. Thanks to enhanced computational hardware and software as well as new machine learning structures, it is now possible to build large models able to reproduce highly nonlinear functions in short times.

This study aims to investigate the capacity of deep learning to achieve spatio-temporal flood modelling. The combination of spatial and temporal input data to obtain dynamic results of water levels and flows from a machine learning model for applications in flood risk assessments has not been achieved yet. Here, we develop increasingly complex machine learning architectures aimed at interpreting the raw input data of precipitation and terrain to generate essential spatio-temporal variables (water level and velocity fields) and derived products (flood maps) by training these based on hydrodynamic simulations.

An extensive training dataset is generated by solving the 2D shallow water equations on simplified topographies using Lisflood-FP. A series of 10,000 artificially generated precipitation events is used to force the model using 22 domains with different topographies. The water depth and flow fields are saved for each precipitation event. One training example consists of one precipitation event on one topographic grid. As a first step, the machine learning model is trained to reproduce the maximum water depth of a simulation, using limited inputs (precipitation, total volume of precipitation, topography, slope). Figure 1 illustrates the comparison between the hydrodynamic model and one of the simplest machine learning architectures used for one simulation (a fully-connected neural network with 3 hidden layers and 16 neurons per layer) that returns a single pixel output using as inputs the total volume of precipitation, the cartesian coordinates, the elevation, the slope and the average slope within a radius of 2, 4, and 8 grids. the slope averaged around 2, 4 and 8 neighbor pixels.

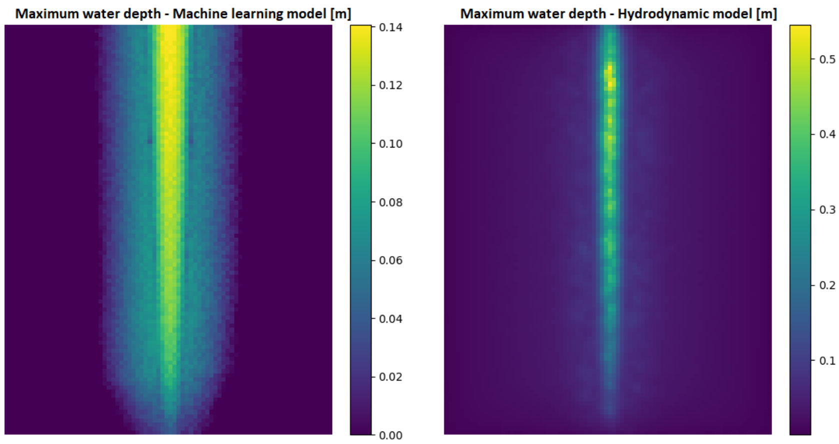

Figure 1. Example of a flood map (maximum water depth) produced by a fully-connected neural network (left) and a hydrodynamic model (right).

As the complexity of the input features and the machine learning model architecture increases, the performance of the machine learning model to approach the hydrodynamic results improves. A major limitation of this approach is the availability of training examples. This is why migration towards deep learning will be essential in further stages of the study.

Assuming that a reliable model can be built and trained, such methodology could be applied to build models that are faster and less computationally demanding than hydrodynamic models. These data-driven models could be used for interpolation and forecasting. The potential for extrapolation beyond the range of training datasets will also be investigated (different topography and high intensity precipitation events).

Keywords: *Hydrodynamic modelling, machine learning, neural network, deep learning*

EXTENDED ABSTRACT ONLY

Predicting the initiation of plot-scale overland flow from surface water coverage and microtopographic depression filling

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Abstract: Irrigation is key to maximising productivity and profitability of dryland pasture systems but over-irrigation can lead to an accumulation of surface water, which in turn results in overland flow and a high risk of contaminant loss. Irrigation-induced overland flow can arise either when the irrigation intensity is higher than soil infiltrability or when the soil becomes saturated. Once overland flow is generated, by whichever mechanism, there is the potential for the rapid mobilisation of nutrients and microorganisms from the soil. Studies have shown that overland flow considerably affects hillslope and catchment runoff and is also the main driver for transport of a range of pollutants to surface-water bodies. Minimising irrigation-induced overland flow is therefore key in reducing contamination and eutrophication of water bodies.

On a rough, but relatively flat soil surface, the initiation of overland flow is delayed until microtopographic depressions are filled. As water ponding in the depressions increases, hydrological connectivity of the field also increases, and this leads to overland flow. When the depressions become full, a sharp increase in overland flow is observed. This phenomenon has been described as a threshold-based runoff response. The detection of this threshold is a way to simplify the description of the complex process of overland flow generation. More importantly, the use of variable rate irrigation technology in conjunction with continuous monitoring of changes in depression storage during an irrigation event, has the potential for minimising overland flow. Continuous monitoring of changes in depression storage (D_s) during an irrigation event is exceedingly difficult. Therefore, an easily measurable variable that can replace D_s is desirable.

We propose that the proportion of the soil surface covered in water (A_{sw}), which is relatively easily measurable using proximal sensing, as a proxy for hydrological connectivity. The proposed method links A_{sw} with the proportion of the surface area connected to the outlet (connectivity). As A_{sw} increases, we expect that there will be a sharp increase in overland flow when A_{sw} reaches a critical value. To examine how A_{sw} affects overland flow initiation, we selected two field plots with different degrees of surface roughness. Each plot had an area of ~1.5 m^2. Very fine resolution (1 mm x 1 mm) digital elevation models (DEM) were obtained using a downward-facing 3D structured light camera (Intel RealSenseTM Depth Camera D415) for each plot. An overland flow experiment was carried out for plots under various rainfall intensities generated by a rainfall simulator. Outlet discharge and changes in A_{sw} (i.e. depression filling, merging and spilling processes) were recorded during the experiment. A ponding and redistribution overland flow model with a surface water coverage estimation function added to it was then used to model the overland flow and the simulation results were compared against the measured data. Simulated spatial distributions of A_{sw} compared favourably with observed values. For both plots, overland flow initiation was controlled by a process of depression filling (i.e. increase A_{sw}) and characterised by a distinct connectivity threshold. Our results showed a clear threshold response of overland flow to A_{sw} (Figure 1). We argue that a significant proportion of the complexity in overland flow processes may be simplified in terms of thresholds that define the gross behaviour of the system. This new recognition of an A_{sw} based runoff response may be a way forward in minimising irrigation-induced overland flow.

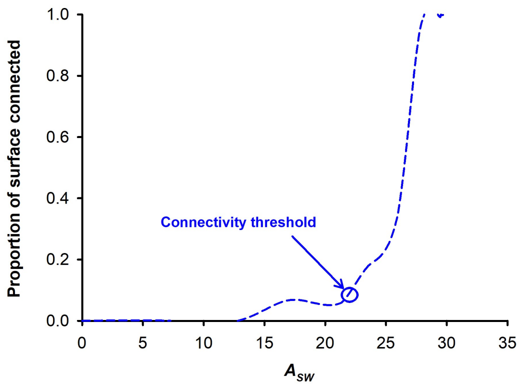

Figure 1: Connectivity as a function of A_{sw}

Keywords: *Irrigation, overland flow, surface water coverage, threshold runoff response*

On the use of remote sensing observations for improved modelling of floodplain inundation dynamics

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Abstract: Floods are among the most devastating natural hazards, affecting multiple regions and millions of people each year. Accurate modelling of spatiotemporal patterns of floodplain inundation dynamics are essential to improve flood risk estimation, increase resilience, and allow equitable management of land and water resources. Evaluation and validation of two-dimensional floodplain inundation hydraulic models has traditionally suffered from data scarcity. However, the recent increasing availability of spatially distributed remote sensing observations provides opportunities for novel methods of model evaluation with the potential to enable more accurate predictions of floodplain inundation dynamics. Nevertheless, further research on evaluation protocols, performance metrics and data uncertainty is essential to effectively exploit the large information content provided by the synoptic view of remote sensing acquisitions.

This study has (i) identified effective ways to use remote sensing data for the evaluation of flood forecasting hydraulic models; and (ii) developed a remote sensing-based methodology to refine the model parameter space (mainly, river roughness) and hence improve the accuracy of floodplain inundation predictions. Two flood events occurred in January 2011 and February 2013 in the Clarence catchment (NSW, Australia) were used as case studies. The selected two-dimensional, raster-based hydraulic model is based on LISFLOOD-FP which uses the finite difference method to solve the inertial approximation of the shallow water equations. Available remote sensing data included both radar (Synthetic Aperture Radar) and optical remote sensing acquisitions.

The results of the numerical analysis showed that, as opposed to point-scale information provided by traditional gauged data, the combined use of remote sensing-derived flood extent and remote sensing-derived wet/dry boundary points allows more coherent and explicative modalities for hydraulic model evaluation. Moreover, a rapid methodology for the assessment of event-specific effective values of the river roughness parameter was proposed. According to this methodology, first, the comparison between modelled and remote sensing-derived wet/dry boundary points can guide the constraint of river roughness values within the footprint of the remote sensing acquisition. Second, the comparison between modelled and remote sensing-derived inundation extent can be used to assess the river roughness values outside of the footprint of the remote sensing observation. Importantly, the proposed methodology relies solely on remote sensing-derived data and it can be applied to ungauged catchments. Furthermore, it must be noted that, as opposed to well-established model evaluation methodologies through Monte Carlo simulation, the proposed methodology was designed to allow a reduced number of model realizations and hence limit the computational cost.

Clearly, testing of the proposed methodology on a larger number of catchments and flood events is required. Furthermore, in a real case scenario, the impact of uncertainties in remote sensing-derived observations on the use of these data for model evaluation has to be carefully investigated. Nevertheless, this research showed the potential benefit of using remote sensing-derived observations of flood extent and wet/dry boundary points to improve floodplain inundation predictions.

Keywords: *Hydraulic modelling, remote sensing, flood extent, model evaluation*

Application of network approach in regional flood frequency analysis

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Abstract: Regional flood frequency analysis is one of the most important and commonly-utilized approaches in water resource management and design of hydraulic structures, especially for ungauged or partially gauged basins. It is the recommended approach to adopt as long as the catchment has not undergone change and a regional flood frequency analysis method has been developed and validated for the region. A crucial step in this approach is to transfer the available information from gauged sites to ungauged sites. It is usually achieved by the delineation of homogeneous regions for the ungauged sites. The homogeneity between the target site and its neighbourhood is normally determined based on a few basic strategies, including evaluating the similarity, relationships, or connections by considering available physiological and meteorological information between them. Correspondingly, in the context of connections or relationships, network theory has established its significance in investigating both spatial and temporal connections and relationships of hydrological variables based on the way of constructing different networks.

In this regard, the present study evaluates the performance of network theory in delineating homogeneous neighbours for a group of 202 catchments in Australia. The results are evaluated by (1) comparing the derived flood quantiles and identified homogeneous neighbours from network theory with those obtained by another widely-accepted method, canonical correlation analysis (CCA), and (2) the accuracy of estimated flood quantiles by applying a simple log-linear regression model which transfers information from two different groups of homogeneous neighbours (i.e. generated by network theory and CCA respectively). Results of the study indicate that network theory offers an attractive alternative to the CCA in identifying homogenous regions, whose use results in a distinctive improvement in the regional flood frequency analysis relationships that are developed.

Keywords: *Complex network theory, regional flood frequency analysis, delineation of homogeneous regions*

EXTENDED ABSTRACT ONLY

Developing a framework to derive river morphology attribute from remote sensing

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Abstract: River morphology is intimately tied to hydrological, biogeochemical, and ecological processes in floodplain–river systems. River width, among the variables affecting hydromorphology, plays an essential role in river discharge estimation, river conveyance capacity assessment, and, in particular, river routing improvement in models. In hydrological modelling, river width is either ignored, set to a constant value, or left as a calibrated parameter. Some regional and global models applied empirical functions to estimate river width from river discharge or drainage area, but these relationships vary in different climate and geomorphological conditions. Digital elevation models (DEM) have also been used in models to reflect river morphology, but their resolution limitations pose a challenge to provide details of river channels features. Although there are some regional or global river width datasets, they do not consider temporal variability of river width, or river width beyond overbank flow threshold conditions. We present a framework to derive temporal and spatial river width dynamics (e.g. Figure 1), flow regime, and river gradient, which can be directly used in models to improve river routing. Water Observation from Space (WOfS), a 25-m resolution Landsat-derived dynamic water mapping product, and the Australian Hydrological Geospatial Fabric (Geofabric), a digital database of spatial catchment, river, lake, and aquifer features based on a Geographic Information System (GIS) platform were used. Each of the 1.4 million Geofabric sub-catchment boundaries across Australia was used to select the targeted area. Inundation extents at different recurrence frequencies within the boundary were calculated from the WOfS inundation frequency mapping for each corresponding river segment. Effective river widths at different recurrence frequencies for 1.4 million river reaches were then estimated by dynamic inundation extents divided by the geodesic length of river segment. We used the Weibull inverse survival function to fit the relationship between recurrence frequencies and width fraction, derived by temporal river widths divided by maximum river width. The parameter of this function was proposed to describe the shape of the frequency–width relationship and can be used to classify reaches by the degree to which flow regime tends towards permanent, frequent, intermittent, or ephemeral. River gradient was calculated by the 1 second STRM derived DEM elevation difference between upstream and downstream points divided by river length for each river reach. The dataset is available at https://doi.org/10.25914/5c637a7449353. The frameworks provide promising opportunities to develop river hydromorphology data for any region of the world with good quality DEM-derived river and catchment features and high-resolution inundation mapping.

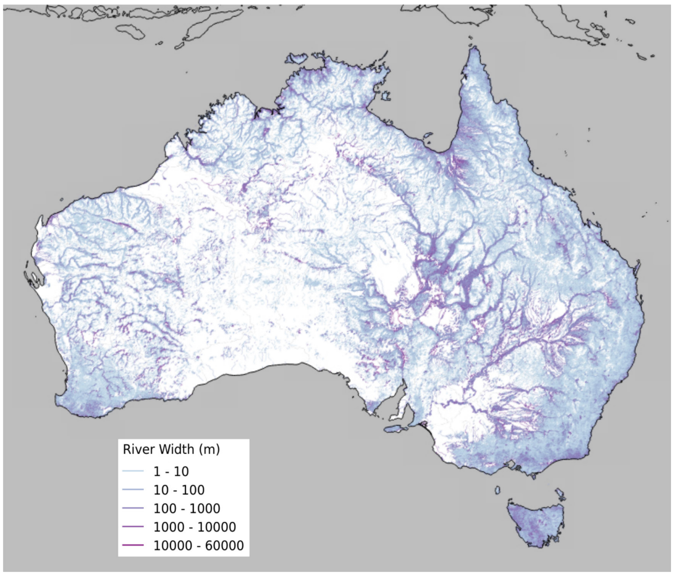

Figure 1. Maximum river width for all Australian river reaches.

Keywords: *River width dynamics, flow regime, river gradient*

Informing planning of River Murray operations by modelling the Lake Bonney/Loch Luna wetlands

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Abstract: The River Murray provides a vital source of freshwater for human consumptive and agricultural purposes, as well as supporting a vast ecosystem of wetlands and diverse habitats. Prior to development in the Murray–Darling Basin, river levels were highly variable as high and low flow periods were encountered, depending on the prevailing climatic conditions. This natural variability has been greatly reduced however with the construction of weirs and locks along the river system and increasing extractions for human consumptive purposes, resulting in a degradation of the river ecosystem over time. Varying the operations of the locks and weirs allows for some of this natural variability in water levels to be reinstated.

Varying the Lock 3 weir pool level presents potential water quality issues through the Lake Bonney and the Loch Luna wetlands, located near Barmera in South Australia (see Figure 1). The lake has been generally more saline than the River Murray since the construction of the locks and weirs, due to evapo-concentration and groundwater discharge processes. In recent times it has held an electrical conductivity (EC) of ~7000 to 8000 μS/cm, but has been observed to rise as high as ~20 000 μS/cm during a period of extended drought conditions. This higher salinity water can be drawn out from the lake under falling river levels, such as when a weir pool is lowered or on returning to normal pool level from a raised position. This higher salinity water can potentially impact on water quality in the Loch Luna and Chambers Creek wetlands as well as the main river channel for local and downstream water users.

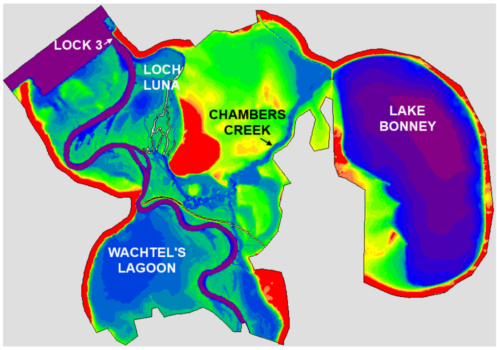

Figure 1. Flexible mesh model domain

To develop an understanding of salinity behaviour under conditions where water levels in the Lock 3 weir pool are raised or lowered from their normal levels, a hydrodynamic Flexible Mesh (FM) model was developed using the MIKE FLOOD package. The model was based on an existing FM model covering from Lock 3 to Lyrup. The mesh, shown in Figure 1, was refined and updated with additional bathymetry data, and sensitivity tested using observed River Murray hydrographs from recent events in conjunction with satellite imagery of inundation extents.


Figure 2. Example model calibration output

The transport module was incorporated in the model configuration to provide the capacity for salt transport through the wetlands to be simulated. Spatial EC survey data at various dates were used to calibrate the transport parameters. An example of the modelled EC distribution from the calibration runs is shown in Figure 2, with red representing high EC, transitioning to low EC in blue. The value of the model for assisting with future planning on operations at Lock 3 with respect to salinity impacts from Lake Bonney was further demonstrated with simulation of some preliminary weir pool raising (WPR) scenarios. Additional salinity survey data and observations of the effects of weir pool variations at Lock 3 will provide further data to enhance the calibration of the model and increase its value as a tool for future operations planning.

Keywords: *River Murray, salinity, hydraulic modelling, river management*

Evaluation of satellite-based land surface temperature differences for global flood detection

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Abstract: Floods result in loss of life, significant damages to environment and socio-economy. Early warning information therefore is necessary for helping global human relief organizations and national water resource services to response effectively to floods. However, conventional flood warning systems have been limited to use for emergency response because of sparse hydrological measuring, delays in accessing data, and inaccessibility in transboundary rivers. Satellite data provide global coverage and near-real time accessibility, and are often freely available. This suggests that it is possible to use space-based data for detecting or mapping floods in large-scale areas. Tremendous efforts have been devoted to identify potential flooding using remote sensing data but fast and universally robust approach to detect floods has not yet been developed for use in ungauged regions. Previous studies have suggested that the difference in land surface temperature between daytime and nighttime (ΔLST) could be a good indicator for flood monitoring. In dry seasons with low flows, land heats and cools quickly, thus ΔLST is high while during flood events, flood flow increases associated with changes in land conditions and ΔLST decreases. Although this relationship suggests that satellite-based ΔLST can be used to detect floods, the changes in LST and river discharge depend on a variety of local climate conditions, land cover, catchment properties and hydrologic characteristics. Here we evaluate the potential of ΔLST for global flood detection. We investigate the relationship between ΔLST and flood flows across contrasting conditions at global scale. The ΔLST values were derived from 0.05° daily Moderate Resolution Imaging Spectroradiometer (MODIS) Aqua products. Flood flows were extracted from daily Global Runoff Database Center (GRDC) data at more than 3000 stations. Regression trees governed by the different conditions were developed to examine the relationship between ΔLST and flood flows. The results in Australia show that strong negative correlations occurred in the hot and steppe regions. The tropical, monsoon, hot and high dense of vegetation coverage had moderate negative correlations while weak negative correlations were found in cool temperate regions with small catchment areas (Figure 1). The results suggest that the best condition under which ΔLST can be used to detect flood flows are high temperature and sparse vegetation coverage. The findings provide understanding of the conditions under which ΔLST may be useful for detecting floods or developing flood warning systems in large-scale spatial and sparsely gauged areas.

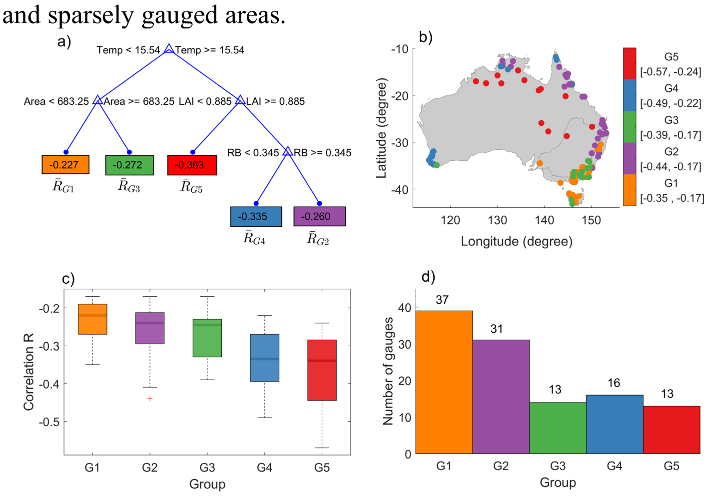

Figure 1. ΔLST-flood flow relationship analysis: a) regression tree with average correlation at each leaf, b) spatial pattern of the correlation with the range of correlations in each group, c) boxplots of the correlation of five groups, and d) number of gauges in each group. Temp is air temperature, Area is catchment area, LAI is leaf area index, and RB is flashiness index. Five colors present to five groups

Keywords: *Land surface temperature, river discharge, flood detection, regression tree, ungauged regions*

Responses of groundwater discharge to climate variation in headwater catchments of the Murray-Darling Basin

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Abstract: Groundwater plays an important role in sustaining both the socio-economic system and ecosystems. The strategic importance of groundwater in water security is intensifying under a changing climate. Climate change could have great impacts on the groundwater system directly through the groundwater recharge process or indirectly through groundwater extraction. These impacts can be propagated to changes in groundwater discharge (i.e., baseflow) to rivers, which will therefore reshape the fundamental functions of the river system especially in maintaining environmental flows. The baseflow in an unregulated and relatively pristine basin is a good indicator of shallow groundwater storage and availability, but also an important metric to measure the connection between surface water and groundwater. The larger the baseflow, the stronger the connection is. Groundwater-dominated rivers are generally considered to have more stable flow regimes that are essential for water supply. Although efforts are increasing to investigate how climate change affects baseflow, our current knowledge of those influences and their relative importance are still very limited due to the differences in catchment characteristics and limited measurements, and hence there is a great need for further investigation.

As one of the most significant agricultural areas in Australia, the groundwater system of the Murray-Darling Basin provides a rich source of sustenance for agriculture, regional communities, and wetland and riverine environments. However, climate change and climate-induced overdrawing have reduced groundwater levels and led to deterioration in the water quality in the river. This study investigated the responses of groundwater discharge to climate variation for 14 unregulated catchments in headwater catchments of the MDB. The groundwater discharge of those catchments were first estimated using a digital filtering approach, based on which the relationship between the discharge and climate variables were investigated followed by sensitivity analysis to quantify the dominant climate drivers for the changes in groundwater discharge.

We found that groundwater discharge in all the studied catchments has been decreasing during the period 1975-2016. A non-linear effect is found between discharge and climate variables. It is estimated that a 10% reduction in potential evapotranspiration will result in ~12% increase in baseflow while 10% decrease in total rainfall will result in over a 24% decrease in baseflow. Groundwater discharge shows more sensitivity to winter rainfall than to other climate variables. Increase in discharge caused by a 10% higher winter rainfall is 2.5 and 1.3 times that induced by similar percentage changes in rainfall in spring and autumn respectively. This climate elasticity of groundwater discharge is quite consistent among the studied catchments.

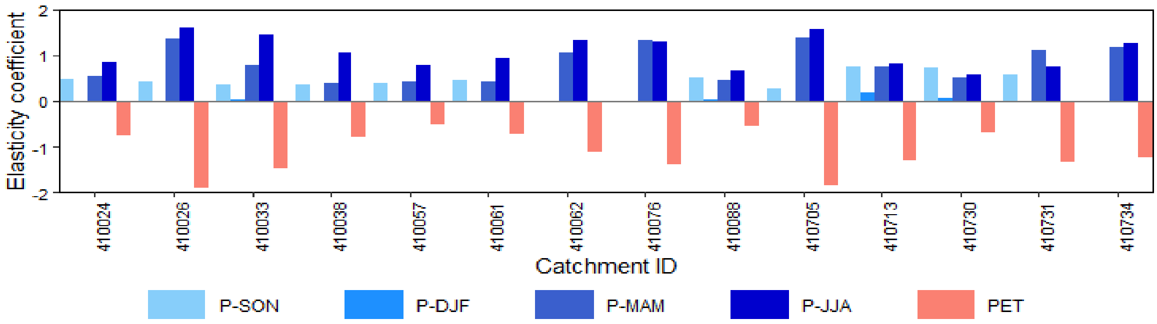

Figure 1. Climate elasticity of groundwater discharge for 14 catchments in the MDB. *P-SON, P-DJF, P-MAM* and *P-JJA* are total rainfall in the spring, summer, autumn and winter, respectively; *PET* is annual potential evapotranspiration.

Keywords: *Groundwater discharge, climate change, climate elasticity, Murray-Darling Basin*

Modelling water table depth in New South Wales groundwater bores

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Abstract: Groundwater systems are the principal source of water supply in Australia. Several regional areas rely on these for irrigation, industrial or urban use. Australia's use of groundwater is expected to grow as a consequence of increases in drought duration, especially in areas where the surface water resources may become less available due to drier and hotter conditions.

However, water abstraction for agriculture and urban use, combined with continued dry climatic conditions might cause a decline in the water table depths. Such a drop in the groundwater levels can have severe impacts on the environment: it further reduces near-surface soil moisture, affects evapotranspiration and hence causes water stress to crops and impacts the land surface energy budget. Therefore, the monitoring of groundwater levels is crucial to maintain agricultural production and natural ecosystems. However, due to the significant time lag between rainfall deficiency and hydrological-drought, bore monitoring alone may not be enough to fully understand the impact of groundwater changes. Predictive models are therefore necessary to understand water table dynamics in different hydrometeorological conditions.

This work aims to reconstruct and predict the water table depth for different groundwater bores in New South Wales. In particular, we concentrate our analysis on different groundwater bores in the Murrumbidgee River Basin. For these locations, we retrieved hourly historical weather data from October 2012 to May 2019 (source OpenWeatherMap). Next, hourly weather information was obtained through direct API calls to the Weatherbit.io website for the period May 2019 to present. In addition, each day we collected 16-day forecasts to compare the performance of the model on actual and forecast water table depth.

To reconstruct the composition and hydrodynamic properties of the soil in the location of interest, we combined data from SoilGrids and BNU China soil data base.

These data provide the boundary conditions for the BioReactive Transport Simulator (BRTSim, [1]) to simulate the water table dynamics forecast. Finally, the output is directly compared with the historical and current water table depth provided by WaterNSW.

***Acknowledgements**: This work was partially supported by the SREI2020 EnviroSphere program of the University of Sydney.*

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Keywords: *Ground water levels, modelling, soil properties*

Assessment of the impact of cyclones on the annual sediment budget in a Pacific Island catchment using a hydro-sedimentological model

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Abstract: Pacific Islands are one of the world hotspots for climate change, with sea level rise (SLR) and increases in tropical cyclones (TC) activity posing a serious threat to coastal areas and ecosystems. Precipitation and extreme sea level events associated with TC generate floods that cause damage to agriculture, home and businesses and also produce considerable amounts of sediment that end up in the adjacent coastal areas. Our study focuses on coastal wetlands that receive sediments from the Dreketi River catchment on the northern coast of Vanua Levu, Fiji which are likely to be heavily affected by climate change. Recent studies have identified this area of the coast as a storm tide high-risk zone, and also that the Dreketi River catchment contributes most of the sediment to the adjacent Great Sea Reef (GSR) or Cakaulevu.

The purpose of this work is to identify the impact of TC on the annual sediment yield through a physically-based hydro-sedimentological model. To address this, the period from 1970 to 2017 was simulated daily with SWAT, obtaining flow and sediment discharges at the outlet of Dreketi River catchment. For the same period, the cyclones within a radius of 600 Km of the barycentre of the catchment were analysed using the Southwest Pacific Enhanced Archive of Tropical Cyclones (SPEArTC). Two types of analysis were performed. The first one focused on the meteorological data, and the aim was to relate the maximum rainfall in the catchment with TC. The second one was based on the results of the hydro-sedimentological model assessing two aspects; i) which percentage of the annual sediment budget can be explained by TC, and ii) in how many cases the maximum annual sediment yield is due to a TC.

Regarding the meteorological data, three meteorological stations were analysed with focus on the maximum daily rainfall. It was found that a TC caused the extreme values in each station in 10, 13 and 15 out of 45 years, respectively. However, the modelling results showed that on average 14% of the total annual sediment yield is related to TC and that TC caused the maximum annual sediment discharge in 19 out of 45 years (42%). These results indicate that even though TCs could not always generate the highest daily value during a year, due to the duration of the event and its intensity they have a significant impact on the annual sediment budget.

Keywords: *Hydro-sedimentological modelling, Pacific Island Nations, tropical cyclones, SWAT*

Improvement of a simplified process-based model for estimating transpiration under water-limited conditions

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Abstract: Soil water deficit is considered the dominant environmental constraint for plant transpiration (and photosynthesis) under water-limited conditions. A simplified process-based model (hereafter BTA) proposed by Buckley et al. (2012) performed well in estimating plant water use under stable water conditions but failed to predict transpiration under varying soil water stress conditions, because it does not account for varying soil moisture conditions. In this study, we improve BTA with both mechanical and empirical approaches. The mechanical method is to include soil water potential (ψ_{soil}) and other two inputs and denoted as the BTA-ψ model. However, it is a challenge to apply BTA-ψ widely because measurement of soil water potential is labor-intensive and time-consuming. An alternative method is proposed by adding an empirical function of volumetric soil water content (θ) to form a hybrid BTA-θ model.

We assess the performance of BTA, BTA-ψ and BTA-θ under subtropical monsoon climate and Mediterranean climate conditions with different levels of water stress. BTA-ψ and BTA-θ performance significantly improves from BTA in transpiration estimation under a wide range of soil moisture conditions at both daily and hourly scales. Species differences in the calibrated parameters of BTA and BTA-ψ models are consistent with leaf-level photosynthetic measurements on each species, as expected given the physiological basis of these parameters. We also test the performance of BTA-ψ in which water potential is derived from soil water retention characteristics and soil water content (referred to as BTA-ψ(θ)). Results indicate that BTA-ψ(θ) is inferior to BTA-θ when parameters of the van Genuchten model were predicted with pedotransfer functions.

As BTA-θ is a hybrid of process-based and empirical components, its performance is expected to be independent of which empirical function is used. Three water stress functions are adopted for BTA-θ and MJS to test the transferability of optimal response function across species and climatic zones. BTA-θ with different water stress functions performs comparably for two climatic zones. The various forms of water stress function in BTA-θ has negligible effect on parameterization of the BTA equation. However, MJS constructed with each of three water stress function performs variably and has a big influence on parameterization of other stress functions. These results suggest that BTA-θ is more robust than MJS in transpiration modelling across sites.

Overall, BTA-ψ and BTA-θ have similar performance for estimating transpiration under a wide range of soil moisture conditions. BTA-ψ is physically more consistent with BTA than BTA-θ. BTA-θ provides a reliable alternative approach to estimate transpiration rates under a wide range of soil water conditions when soil water potential data are not available.

Keywords: *Transpiration modelling, soil water deficit, BTA, water potential, volumetric water content*

Investigation of alternative hypotheses using supplementary binary data

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Abstract: Many water management questions focus on the aggregation of processes to an outlet which can be limited when addressing hydrological questions that are nested across multiple scales (e.g. environmental flows, distributed storages). Process modelling can, in part, address some deficiencies. However process models are restricted by the ability to scale up theoretical understanding and by the ability to quantify parameters that cannot be easily measured. Differences in catchment characteristics result in highly variable drainage patterns, presenting a challenge in the validation of process interactions on the hillslope. This is particularly the case when different combinations of parameters can yield similar results at the outlet.

To compensate for model limitations, alternative hypotheses are investigated with a physical hydrological model and combined with supplementary data. The simulations are assessed to improve understanding of feedbacks and non-linear dynamics across multiple process scales. The physically based hydrological model, HydroGeoSphere, is applied to a small catchment area (10 km^2) that has three tributaries with differing characteristics (e.g. vegetated vs non-vegetated). Four alternative scenarios are calibrated to the outlet with a minimum Nash-Sutcliffe coefficient (NSE) of 0.50 and conditioned to represent four plausible runoff generation mechanisms on the hillslope: (1) Groundwater dominant with saturation excess; (2) Saturation excess dominant with groundwater; (3) Groundwater and saturation excess dominant; and (4) Groundwater dominant with saturation and infiltration excess. Table 1 presents calibrated output and the proportion of runoff mechanism contributing to flow at the outlet for each scenario.

Table 1. Calibrated outputs for the four simulated scenarios, where SE refers to saturation excess runoff, IE refers to infiltration excess runoff and GW refers to groundwater runoff

Alternate hypothesis	1	2	3	4
Runoff scenario	**GW dominant with SE**	**SE and GW dominant**	**SE dominant with GW**	**GW dominant with SE and IE**
Percentage SE	31%	51%	61%	69%
Percentage IE	0%	0%	0%	6%
Percentage GW	57%	46%	35%	19%
Percentage Error	2%	3%	4%	6%
NSE outlet	0.60	0.50	0.50	0.54

The method is supported with inexpensive wet-dry binary data that provides supplementary information on upstream flow intermittency. The four hypotheses are validated with the upstream data by quantifying the correlation coefficient of observed and simulated intermittency patterns. The results in Table 2 demonstrate a reduced performance relative to the NSE at the outlet for at least three out of four upstream sites for all simulated scenarios. There is no single scenario that consistently out-performs other scenarios for all sites. For example, for hypothesis 1 the best performing site is reach 2 (r=0.78) and for hypothesis 2 the best performing site is reach 1 (r=0.78). The results highlight the value of collecting and utilising supplementary data to identify upstream processes with the potential to improve performance by constraining the model.

Table 2. Performance metrics of the four simulated runoff scenarios

Alternate hypothesis	1	2	3	4
Runoff scenario	**GW dominant with SE**	**SE and GW dominant**	**SE dominant with GW**	**GW dominant with SE and IE**
Binary correlation coefficient				
Outlet	0.65	0.16	0.76	0.46
Downstream reach 1	0.27	0.78	0.59	0.33
Upstream reach 1	0.33	0.62	0.47	0.39
Upstream reach 2	0.78	0.38	0.42	0.77
Upstream reach 3	0.36	0.61	0.81	0.43

Keywords: *Process modelling, binary data, alternative hypothesis*

Groundwater sustains water and carbon fluxes in natural urban reserves: The case of Melbourne

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Abstract: In cities, vegetated surfaces often become fragmented into small and isolated patches of native species, which are embedded in a highly disturbed environment with typically altered hydrologic regimes and higher temperatures than the rural surrounds. While the role of trees in supporting urban ecosystem functionality through the provision of ecosystem services is well documented, less is known about their response to environmental stressors, such as droughts and increased temperatures. Recent studies have shown that groundwater can largely sustain ecosystems during seasonal and inter-annual droughts. However, most studies on groundwater dependent ecosystems focus on bio-diverse natural environments or areas mildly affected by human activities, while urban ecosystems sustained by groundwater have received considerably less attention.

This study investigates how different scenarios of groundwater availability control the water balance and vegetation productivity in two urban reserves hosting native vegetation in Melbourne, Australia. A series of numerical experiments were carried out using the ecohydrological model Tethys-Chloris, which simulates essential components of the hydrological and carbon cycles, resolving energy, water, and carbon fluxes at the land surface. Long-term simulations supported by field observations (i.e., soil moisture profiles, groundwater levels, and tree transpiration) were used to explore ecosystem relationship to water availability in the present climate, including the Millennium Drought (2001-2009), and in response to perturbations in key environmental variables (i.e., air temperature, atmospheric CO_2 concentrations, and rainfall).

Results showed that the presence of shallow water tables within the reach of roots support tree transpiration and vegetation productivity (Figure 1). The effects of declining groundwater levels were found to be more severe in predominantly sandy soils because of the lower water-holding capacity. In reserves with different plant functional types, the various root depths and degrees of accessibility to groundwater also had a pivotal role in helping plants soften the impacts of increased air temperature and make use of higher atmospheric CO_2 concentrations. Increased air temperature strongly affected evapotranspiration, enhancing the competition for water between vegetation types.

These results provide quantitative insights on how vegetation responds to groundwater depletion and climate variability, highlighting the essential role that a proper management of groundwater resources might have in urban ecosystems characterized by seasonally dry climates.

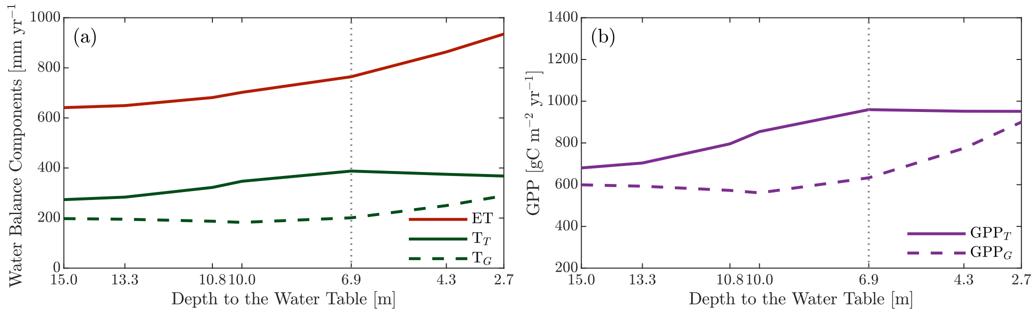

Figure 1. Simulation results averaged over a 19-year period (July 1999 - June 2018) showing: (a) water balance components as a function of depth to the water table, including total evapotranspiration (ET), tree transpiration (T_T), and grass transpiration (T_G); and (b) gross primary productivity (GPP; for unit of ground area) for trees (GPP_T) and grass (GPP_G).

Keywords: *Urban reserves, groundwater dependent ecosystems, ecohydrological modelling, drought*

Predictive modelling of vegetation responses to water availability along the lower River Murray

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Abstract: The abstraction of water for irrigation, consumption and power generation has enhanced the water stress of floodplain ecosystems worldwide. In the Murray-Darling Basin, there is an ever-increasing number of stakeholders competing for a limited supply of water, leaving less water for the environment. As part of the *Basin Plan 2012*, there is an increased focus on supplying water to the environment for ecological benefits through 'environmental flow' projects. As a result of this policy shift, there is an increased need to predict ecosystem responses to environmental flows, and the benefit that additional water provides to floodplain ecosystems. The traditional approach to monitoring vegetation responses is through observing vegetation indicators such as tree canopy condition at tree or plot scale. The large extent of the Murray-Darling Basin (1 million km^2) makes detailed monitoring of individual trees using more robust methods such as sap flow, expensive and spatially constrained. This means there is a need to extend the usefulness of existing data sets and to incorporate new data, such as remote sensing observations, to rapidly assess large spatial extents. This project seeks to incorporate available data sets to produce a novel predictive model for understanding floodplain vegetation responses at scales relevant to inform policy and provide a tool for water managers.

Our model incorporated scarce, fine-scale measurements of tree water use with broad-scale climatic and hydrological data, to model vegetation responses accurately across large areas. Sap flow measurements collected from four sites across the lower River Murray were used, which monitor daily tree-scale transpiration over time. Sap flow sensors are a costly but rigorous method by which to monitor environmental responses. Broad-scale climatic and hydrological data were combined with monitoring data in a random forest model to determine general predictors for sap flow. Random forest modelling is suited to large ecological data sets and can provide a simple model which can be applied across large areas. More specifically, the method takes advantage of correlations between fine-scale measurements and coarse climatic data to extend the existing fine-scale data set and provide a platform to predict vegetation responses to different conditions and different locations.

Current results indicate that the model successfully identifies key variables, and models vegetation responses accurately across the test sites, providing a clear modelling framework. The model successfully captures the detail of complex interactions between vegetation, climatic and hydrological factors. This model is effective at a small scale, but to be a relevant tool for water manages, it must perform at broader scales. Extending the model outside of the test sites to areas without tree-scale measurements will indicate if there is a uniform relationship between plant responses, climatic and hydrological variables across the Basin. The ability to predict vegetation responses to environmental water on a relevant scale will allow policy makers and water managers to better distribute water for the environment.

Keywords: *Random forest modelling, environmental flow, Murray-Darling Basin, predictive modelling*

Analysing the effect of climatic variations on soil carbon redistribution using a coupled dynamic vegetation, carbon pools and landform evolution model

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Abstract: Soil erosion redistributes soil organic carbon (SOC) through the landscape; however, there is limited understanding on how geomorphology, topography, and vegetation affects erosion and SOC redistribution. Current erosion studies disregard feedbacks between erosion, vegetation and soil carbon and most carbon cycle models assume no lateral fluxes (i.e., the carbon mobilized by erosion). Climate change will result in changes of soil erosion and deposition rates, alterations of the SOC distribution and increase in soil respiration rate, which will modify the amount of stored carbon in the soil. For example, climate change projections for the north part of Australia (for a scenario with carbon dioxide concentration of 940 ppm by 2090) include a change between +23 and -26% in rainfall and an increase of 3.7 degrees in temperature. Such changes will require understanding the influence of erosional/depositional processes on the carbon cycle in order to develop strategies to mitigate climate change. In this work, we use COPLAS, a model that couples hydrological, geomorphological, and biogeochemical processes and their dynamic feedbacks. The model tracks the allocation, distribution and transformation of carbon from photosynthesis to soil carbon. COPLAS uses biochemical-coupled equations of photosynthesis-stomatal conductance and respiration representation that respond to climatic data inputs of temperature, CO_2 concentration and water availability. We use our model to quantify the impact of variations on rainfall and temperature on the soil carbon redistribution at the catchment scale in Howard Springs (Northern Territory, Australia). The model is first validated using Ozflux historical data and carbon balance estimations. Six climate change scenarios are then run for high, low and normal rainfall, and normal and elevated temperature. Each simulation was carried out for 100 years using a daily time step. We found that, for our study case, higher amount of rainfall mobilized more soil carbon because of the increases in erosion rates. Soil carbon tend to deplete when concentrated flow occurs and accumulation areas start to be appreciable. A strong reduction (almost half) in soil carbon was obtained when we included the effect of temperature due to increase in soil carbon respiration and evapotranspiration. This is a result of greater soil carbon degradation and CO_2 release to the atmosphere (spatially varied in the catchment) and less soil moisture available, that limits vegetation growth, litter and carbon stored in the soil. These findings highlight the importance of including a better vegetation and carbon representation to understand the effect of climate and erosional/depositional processes on the carbon cycle.

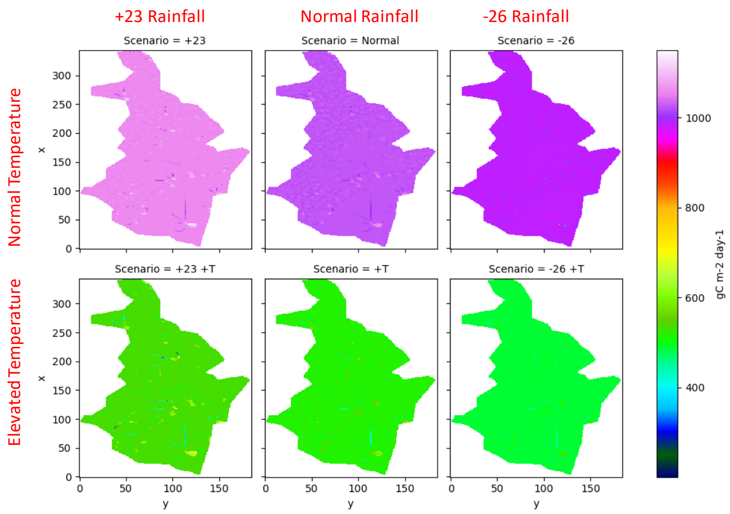

Figure 1. Soil carbon spatial distribution for normal and increased scenarios of rainfall and temperature.

Keywords: *Soil carbon, erosion, vegetation, carbon cycle*

Comparing transpiration changes of three tree species based on hydraulic strategy in a semi-arid region

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Abstract: As precipitation and temperature patterns continue to shift due to climate change, understanding if and how ecosystems and their different plant species will survive is crucial. Plants exchange water for carbon through the process of transpiration, the largest component of the terrestrial water cycle for many ecosystems. We hypothesize that species with the most advantageous hydraulic traits and strategies are the most well adapted to survive. Here we use a plant hydraulics model in combination with a field study to (1) determine which hydraulic strategies are being used by different species and (2) test if these traits will better enable plants to survive local droughts.

This study uses micrometeorological and sap flux data, collected using Granier-style sensors, to quantify transpiration rates in three tree species (*Pinus remota*, *Quercus virginiana*, and *Juniperus ashei*) on a semi-arid ranch located near Rocksprings, Texas, USA. We use these data with the finite difference ecosystem-scale tree crown hydrodynamics model version 2 (FETCH2) in order to better understand the hydraulic traits of our three study species. FETCH2 utilizes finite difference numerical methodology to determine water xylem potentials throughout a tree. Based on the assumption that xylem functions similarly to porous media, FETCH2 uses the Richards equation to account for the conductance and capacitance of the tree's hydraulic system with changes in water potential. The model can be parameterized with measured plant hydraulic traits such as xylem conductivity, isohydricity, and rooting depth to simulate the trees' different hydraulic strategies. We employ the model as a sensitivity test to analyze which suites of plant hydraulic traits are the most deterministic of the trees' observed transpiration patterns. We further expand our analysis by using the parameterized model to simulate site-wide changes in transpiration if precipitation patterns change and our study site becomes increasingly arid.

Model simulated transpiration provides insight into how our tree species obtain and utilize water. By comparing the hydraulic traits and the resulting parameter sets, we can enhance our understanding of hydraulic strategy and its influence on total transpiration as well as transpiration in response to simulated and observed droughts. As the climate continues to warm and precipitation patterns become increasingly variable, a mechanistic understanding of and ability to model species-specific vegetation responses to drought will be crucial for predicting water and carbon fluxes.

Keywords: *Transpiration, hydraulic strategy, plant hydrodynamics model, sap flux*

Tree-hydrodynamic modelling of *Eucalyptus globulus* for plantation assessment

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Abstract: The change of land use from pasture to plantations is perceived as a dramatic stressor on water resources. The establishment of plantations can increase the pressure on water resources due to a greater interception of rainfall, higher transpiration rates, and deeper root depths that can reduce groundwater recharge and modify the water balance. For these reasons, water-use by plantations is accounted for to regulate plantation establishments in South Africa and South Australia.

In Australia, plantations occupy an area of approximately 1,955,100 ha, with 51.7% of the plantation areas in the country being cultivated with *Eucalyptus globulus* (blue gum), which is the dominant species for hardwood production. The blue gum is a fast-growing tree, capable of growing in a wide range of environmental conditions, with high potential for carbon sequestration and wood production. Even though plantations are widely planted in Australia, the water accounting models used for forest management adopt an annual time-step over the entire management cycle, averaging the impacts and not accounting for seasonal patterns of actual transpiration. Additionally, the water used by plantations in the early years after establishment is not well studied and thus difficult to estimate.

This study aims to use a tree hydrodynamic model, supported by field observations, to simulate water fluxes across the soil-plant-atmosphere continuum in *E. globulus* trees. The model employed in this study is FETCH2 (the finite difference version of the Finite Element Tree Crown Hydrodynamics), which has been implemented in Python 3.7. Assuming the xylem to be a porous medium, FETCH2 describes the water flow between soil and roots and along the xylem using the Richards equation with sink and source terms for transpiration and root water uptake. The key features of FETCH2 include a coupled representation of the soil, roots, and xylem hydraulics by assuming the flow follows a path of decreasing water potentials. The simulated transpiration in FETCH2 realistically accounts for the water storage within the xylem. Additionally, the parameters used in the model are representative of traits that control aspects of the plant hydraulic response, such as hydraulic redistribution and root water compensation.

The model was applied to two different *E. globulus* plantations located in southwestern Victoria, Australia, within the Glenelg River Basin. The first site, referred to as Gatum plantation, has mature trees about 13 years old, and the second site, referred to as Digby plantation, has trees younger than 3 years. Meteorological data for both sites will be used as input to the model. Physiological species-specific parameters are calibrated using sap-flow measurements in a few months of 2017 and 2018 at Gatum, and eddy-covariance measurements of latent heat flux as well as sap-flow data in 2019 at Digby.

The results show the effectiveness of a tree hydrodynamic model for the description of water fluxes across the soil-plant-atmosphere continuum and for the generation of reliable and realistic estimates of tree transpiration for different water availability periods. Applying this model to different water availability scenarios can result in a more precise assessment of temporal and spatial water use for plantations in Australia, supporting their sustainable management.

Keywords: *Plant hydrodynamic model, Eucalyptus globulus, ecohydrology*

Aspect-controlled spatial and temporal soil moisture patterns across three different latitudes

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Abstract: Soil moisture in semi-arid areas plays a critical role as it regulates numerous ecohydrologic processes in land surface hydrology, subsurface hydrology, and vegetation dynamics. Studies on soil moisture distribution and dynamics currently rely on data obtained using three types of approaches: in situ (generally point-scale) measurements, remotely sensed observations, and modelling approaches. The spatial variability of soil moisture plays a vital role in the estimation of land surface fluxes (evapotranspiration (ET) and runoff) due to the non-linear relationship between soil moisture and the associated physical processes. Understanding this variability is essential for the optimal management of water resources and ecosystem sustainability. Although a considerable amount of work has been done on the subject, the ability to understand and characterize the mechanisms that determine the distribution patterns of soil water content still remains a challenge at the centre of hydrological research, especially for ungauged catchments. It is necessary to understand the spatial variability of soil moisture and its influencing factors, which will provide a basis to improve our understanding of hydrological, biogeochemical processes, and lateral and subsurface flow processes.

The effects of several factors that control soil moisture variability (SMV) in semi-arid landscapes (microclimate, vegetation, topography, soil depth, soil texture, etc.) have been documented in previous work. However, the control of latitude on SMV under different environmental conditions still remains poorly understood. Latitude significantly affects the availability of water and energy as the global distribution of solar radiation varies from the equator to higher latitudes. Latitude has a dominant control on the availability of water because of the varying amount of solar radiation on north-facing slopes (NFS) and south-facing slopes (SFS), which influences soil moisture variations. This study focusses on evaluating and comparing the effect of latitude on SMV, and its control on soil moisture patterns. To this end, we use a modelling framework to capture the joint effects of aspect and latitude on SMV.

We used the Bucket Grassland Model (BGM), equipped with a vegetation dynamics component, to analyse soil moisture patterns and variability at various latitudes (45°N, 34°N, and 15°N). The main objective of this study is to investigate changes in soil moisture patterns at various latitudes and differences in SMV on the different aspects for a synthetic domain. We conducted different simulations as a sensitivity analysis (at various latitudes) using BGM to study the effect of aspect-related soil moisture variations in a semi-arid landscape. The latitudinal patterns of modeled soil moisture are analysed, and distinct variations are identified in the SMV.

The results show that water stress varies with aspect and are affected by latitude, which in turn affect the SMV. Further, they show that SMV increases moving towards higher latitudes. Also, aspect-related soil moisture differences are enhanced at higher latitudes. Therefore, it is not possible to characterize soil moisture variations or model surface hydrological processes at the catchment scale, without explicitly accounting for aspect, particularly in ecosystems where the aspect has a dominant effect.

Keywords: *Soil moisture, aspect, latitude, vegetation dynamics*

INVITED PAPER

EXTENDED ABSTRACT ONLY

Shifts in rainfall-runoff relationships: how did they change across Australia?

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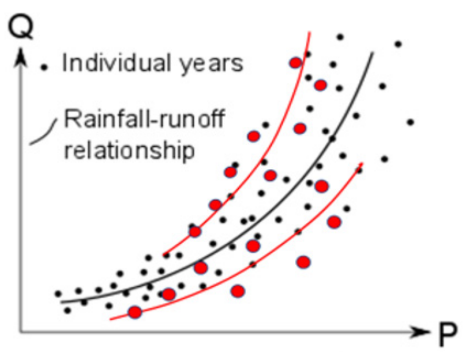
Abstract: Managing water resources within Australia's highly variable hydroclimate remains an ongoing challenge. Recently, a drying trend has been most evident in the southwestern and southeastern corners of the country, where a large proportion of Australia's population live. Previous research has shown that many Australian catchments display patterns of disproportionately large changes in streamflow in response to declining rainfall. This was particularly observed during and after prolonged drought conditions. In contrast, in northern Australia streamflow has increased in areas where rainfall has shown increases.



Giving these changes in climate in Australia, water managers, planners and policy makers need to know what rainfall patterns are capable of delivering in terms of streamflow. In Australia this knowledge is vital, given Australia's high dependence (> 80%) on surface water for its water supply. The Bureau of Meteorology, as Australia's national weather and climate agency, and the University of Melbourne have partnered to investigate and provide better understanding of the changes in surface water resources in response to climatic changes and other drivers. Using extensive rainfall-streamflow datasets representing Australia's range of hydro-climatic variability, we use statistical approaches to systematically investigate where and how shifts in rainfall-streamflow relationships have occurred. Building on the work of Saft et al. (2015; 2016), changes in rainfall-runoff and climate-runoff relationships over the long-term as well as seasonal periods will be investigated across the 600 selected catchments using regression-based approaches The previous work of Saft et al. (2015; 2016), which focused on changes in rainfall-runoff relationships during the Millennium Drought in South-Eastern Australia. In addition, Saft et al. (2017) investigated the trends in changing rainfall-runoff and climate-runoff relationships along with changes in climatic variables around the world, including Hydrologic Reference Stations (HRS) catchments in Australia.

This work focusses on long-term and seasonal trends in the rainfall-runoff and climate-runoff relationships for a large dataset of Australian catchments including regions experiencing significant trends in climatic characteristics. Following identification of changes in the rainfall-runoff relationships, an analysis of hydroclimatic features and their relation to catchment characteristics will be undertaken to assess likely mechanisms for these changes in hydrologic response. Streamflow and rainfall data are used for modelling with data beginning in 1970 or earlier. Contextual data on catchment land use, soils, topography and other biophysical factors is also used to understand drivers of change. Our findings can be used to better characterise and manage freshwater resources under varying climates. This research will build publicly accessible services around water resources availability to help raise awareness and assess risks related to future availability and security of streamflow.

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Keywords: *Changing rainfall-runoff relationships, changing climate and hydrologic trends, Australia*

Flip the bucket: why models based on deficits, not buckets, may be needed for runoff projections in a drying climate

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Abstract: Rainfall runoff models based on conceptual "buckets" are frequently used in climate change impact studies to provide runoff projections. Here we present an alternative deficit-based "flipped" bucket model and argue that deficit models are inherently more capable than bucket models at providing runoff projections under drier conditions. Applying the altered model to 38 catchments in Victoria, we compare simulations to independent data including actual evapotranspiration, groundwater bore data and satellite-based estimates of terrestrial water from the Gravity Recovery and Climate Experiment (GRACE). These comparisons partly confirm the model structural changes (in the case of actual evapotranspiration) and also suggest future ways to further improve the structure (in the case of groundwater and GRACE).

In bucket models, a full bucket means a catchment is wet, while drainage or evapotranspiration cause declines in bucket storage. Since a bucket can be empty (zero storage), such models have a "driest possible state" that may not be reached in reality. When a model approaches empty, evapotranspiration approaches zero, which means the model may cease to properly track the moisture deficit accumulating in reality as dry conditions continue. The incorrect moisture deficit causes overestimation of runoff from subsequent rainfall events, leading to long-term model bias if dry conditions persist for multiple years (or indefinitely under climate change). In contrast, deficit-based models are flipped buckets: the wettest possible state is zero deficit, there is no a priori "driest possible state", and the deficit can keep accruing as dry conditions continue.

Here we prepare a flipped version of the commonly used GR4J model, called GR4J-dd. Judging purely from matching streamflow, the altered model provides superior performance over historic periods of varied climate, including the 13-year "Millennium Drought". The model is better able to transition from wetter climatic periods (eg. the early 1990s) to drier periods (eg. the Millennium Drought) without the need to change parameter values (Figure 1). Furthermore, comparisons with actual evapotranspiration data suggest that simulated AET from the original GR4J model is both less sustained than, and out of phase with, actual AET. The altered model partly corrects these tendencies. Lastly, comparisons with groundwater and GRACE data reveal long-term trends that are not matched in simulations. This is particularly the case in the western half of Victoria, where multi-year decline in groundwater is very common across many bores. In contrast, the original and the altered GR4J model have no multi-year trends in any element and are thus qualitatively inconsistent with observations. Multiple different strategies are discussed to resolve this issue. We recommend further research focus on deficit models (of which many exist beyond that presented here) to improve plausibility of runoff projections for climate change impact studies.

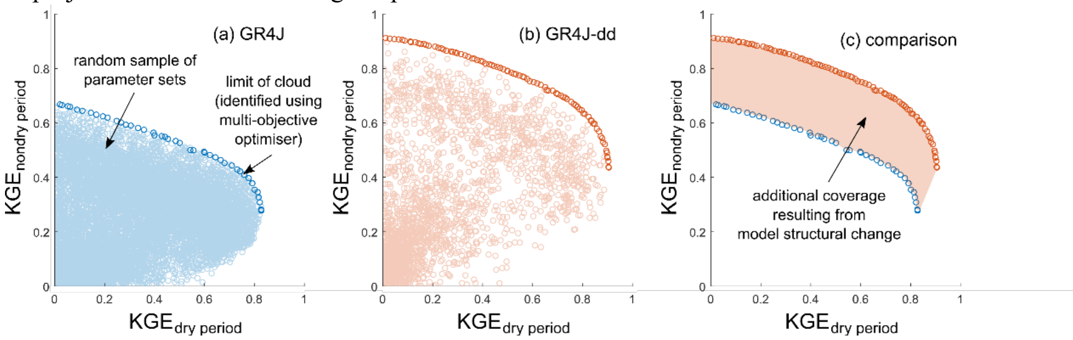

Figure 1. (a) Coverage of a random ensemble of parameter sets for GR4J in 2D model performance space where the x axis refers to the seven driest consecutive years on record (2003-2009) and the y axis is the remaining record, for gauge 406213, Campaspe River at Redesdale (639 km²), Victoria.

Keywords: *Rainfall-runoff modelling, drought, climate change, runoff projections*

Trends in precipitation and temperature in Canberra

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Abstract: The current drought over much of southern and eastern Australia began not long after the Millennium Drought. While the Millennium Drought motivated Canberra to introduce measures to improve water availability, Canberra's population is increasing, placing greater strain on water resources. Further, its latitude is similar to other areas in the world in which drought frequency is increasing. Analysis of precipitation trends is required to assess how vulnerable an area might be to drought. In addition, if the mean temperature of a location is increasing, then the region might become more vulnerable to drought due to increased potential evaporation.

This statistical study utilises resampling methods to analyse trends in precipitation and mean temperature over Canberra. These resampling methods highlight the non-stationary nature of both precipitation and temperature time series. Minimal trends in precipitation were found, however there was an increasing trend in both mean maximum temperature (p-value = 0.0028) and mean minimum temperature (p-value = 0.0358) suggesting an increased vulnerability to drought for the region.

Numerous large-scale influences of climate such as the El-Niño Southern Oscillation (ENSO) have been used in the seasonal prediction of various atmospheric conditions. For example, an El-Niño event is typically associated with warmer and drier than average conditions over eastern Australia. Wavelet analysis provides a more thorough understanding of high- and low-frequency signals driving a non-stationary time series, and is applied here to identify potential drivers of the climate. Wavelet power spectra for precipitation reveal a statistically significant signal in the 2–7-yr range, which is typically indicative of influence by ENSO. Wavelet power spectra for mean maximum temperature reveal an increasing influence by ENSO, while mean minimum temperature reveals a decreasing influence. These findings exemplify how the influence of climate drivers can change over time. Accordingly, there is a need for recurrent analysis of the changing influence of climate drivers across Australia to improve skill in forecasts which utilise these climate drivers.

Keywords: *Canberra, precipitation, temperature, drought, wavelet analysis, permutation testing*

Random walk parameters to model hydrologic non-stationarity

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Abstract: There are few practical methods in dealing with non-stationary systems in water resources planning and management. Often, a system is assumed to have fixed parameters through time. The reliability of hydrologic predictions in such approaches will frequently be poor if the systems change significantly through time. Ideally, these changes are accounted for in the model structure, however, the way the system evolves is often inexplicable. To give better reliability to predictions, distributions of parameters can be obtained through uncertainty analysis, however these usually only consider time-invariant parameters. Time-varying parameters have been used in multiple past studies, but assumptions of stationarity are still implicit in these formulations. Non-stationary conditions are achieved by describing a parameter with a random walk process. Furthermore, much flexibility is provided if a first-order autoregressive (AR(1)) model is used. If we assume the parameter of interest, θ, for time interval, t, is given by:

$$\theta_t = \bar{\theta} + \varepsilon_t \, , \tag{1}$$

$$\varepsilon_t = \varphi\varepsilon_{t-1} + \mathrm{N}(0, \sigma^2) \, ; \quad 0 \le \varphi \le 1 \, , \tag{2}$$

and if the AR(1) parameter, φ, is equal to 0, the parameter error, ε_t, is represented by Gaussian noise. As φ approaches 1, ε_t, becomes more autocorrelated. When $\varphi = 1$, ε_t (and therefore θ_t) is non-stationary. $\bar{\theta}$ denotes the mean parameter value, and σ^2 is the variance parameter for the Gaussian distribution.

A Bayesian uncertainty analysis was used to infer values for $\bar{\theta}$, φ and σ^2. The approach was performed on a time period and site where model structure issues are known to exist (614062, Bates catchment, WA). The soil moisture store capacity parameter (x_1) of the GR4J rainfall-runoff model was used as the time-varying parameter in the proposed approach. As expected, the sampled φ values are close to 1, and sampled x_1 values show potential signs of random walk (Figure 1, green plots). In contrast, for a site where the model performs well in a similar length period (405205, Murrindindi River, VIC), the φ values are more spread and x_1 appears stationary in time (Figure 1, blue plots).

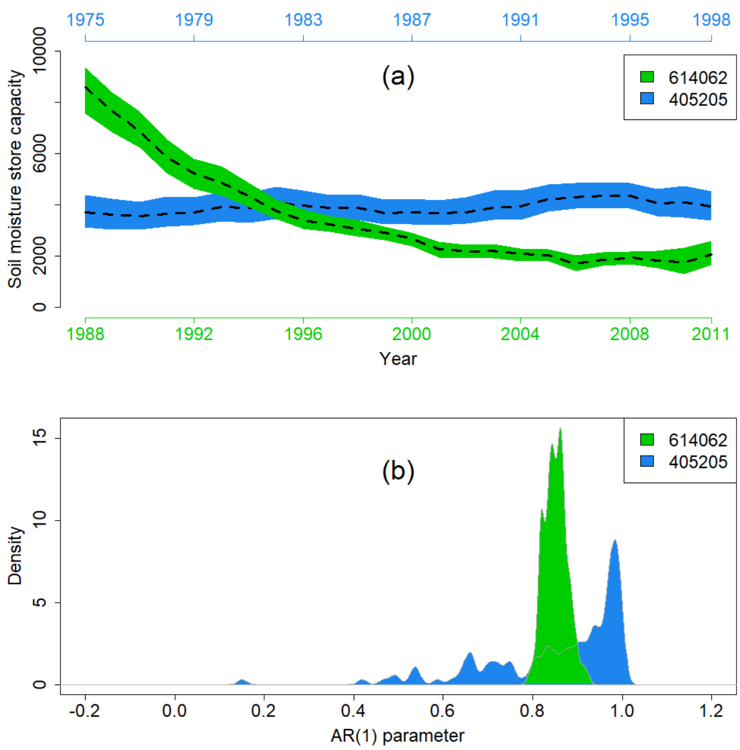

Figure 1. Comparison of the evolution of x_1 (a) and posterior distributions (kernel density estimates) of φ (b).

Challenges arise since prediction ranges will potentially become very large during scenario simulation studies. However, the current approach allows simple and rigorous implementation of these exercises in the absence of better system knowledge.

Keywords: *Bayesian uncertainty analysis, parameter uncertainty, MCMC, non-stationarity, water resources*

Changes in the frequency of Australian rainfall extremes

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Abstract: The risks of extreme rainfalls and floods are changing as a result of climate change. To ensure the risk of failure from flooding is kept to a societally acceptable level, it is prudent that these changes be considered as part of the design of new infrastructure and the management of existing assets. It is now well established that the intensity of heavy rainfall events is increasing as a result of climate change. However, changes in the frequency of occurrence of extreme rainfalls are less well understood. Future increases in the frequency of extreme rainfalls implies that infrastructure that has been designed based on historical flood risk will have a higher risk of failure (under design), while future decreases may lead to over design. Decreases in the frequency of extreme rainfall may also mean longer dry spells and less runoff, reducing the resilience of water supply systems.

Using data from Australian daily rainfall gauges we investigate trends in rate of occurrence (frequency) of extreme rainfalls. For each gauge the number of independent rainfall events that exceed a threshold in each year of record are identified. Trends in these frequency series over time are investigated as well as relationships between the trends and the different metrological drivers of climatic change. Multiple parametric and non-parametric trend tests are applied to ensure identified trends are robust and different thresholds of severity are employed to investigate if the rate of change in frequency varies with event rarity.

Trends in frequency over time are shown to display distinct regional behaviour where some regions exhibit increases in trends and others decreases. These trends are found to vary both with event severity and with regional meteorological variables. The results suggest that unlike extreme rainfall intensity changes which appear to be universally increasing across Australia and the globe, changes to the frequency of extreme events may be governed by changes to the local climatology.

Keywords: *Precipitation, extreme precipitation, frequency, climate change*

Catchment Drought Recovery: A statistical analysis of hydrological resilience throughout Victoria

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Abstract: Surface and groundwater hydrological models behave so that after a disturbance of any magnitude, such as a drought, the system eventually recovers (Peterson et al. 2009). Hence, catchments have been assumed to be infinitely resilient. Recently, this assumption has been challenged and theoretical deterministic modelling has shown that meteorological variability can displace hydrological systems into a self-reinforcing new stable regime; and hence have a finite resilience (Peterson et al. 2012, 2014a,b). However, whether real catchments are infinitely resilient and always recover from disturbances remains an open question.

To begin to answer this question, we statistically identify if and when unregulated catchments in Victoria (n=162) recovered from the Millennium Drought. Hidden Markov Models (HMM) were developed to statistically quantify when the annual (or seasonal) runoff shifted during the meteorological drought, using an approach similar to Saft et al. (2015), and if and when runoff recovers. For each catchment, 64 different annual timestep HMM maximum likelihood estimated models were derived (seasonal: 32 models). The best model was then selected using the Akaike information criterion and the most probable sequence of runoff states was then identified using the Viterbi algorithm. We found that ~30% of the 162 catchments have not recovered from the Millennium Drought (Fig. 1). This fraction appears stable and suggests that recovery cannot be assumed to occur soon. This is consistent with, but not proof of, catchments having a finite resilience to droughts. However, analysing those that have recovered from either the Millennium Drought or the 1982 drought suggests that recovery is possible, but it may not be simply due to catchments wetness, specifically the cumulative monthly rainfall residual. The driver(s) and thresholds for recovery remains an open question.

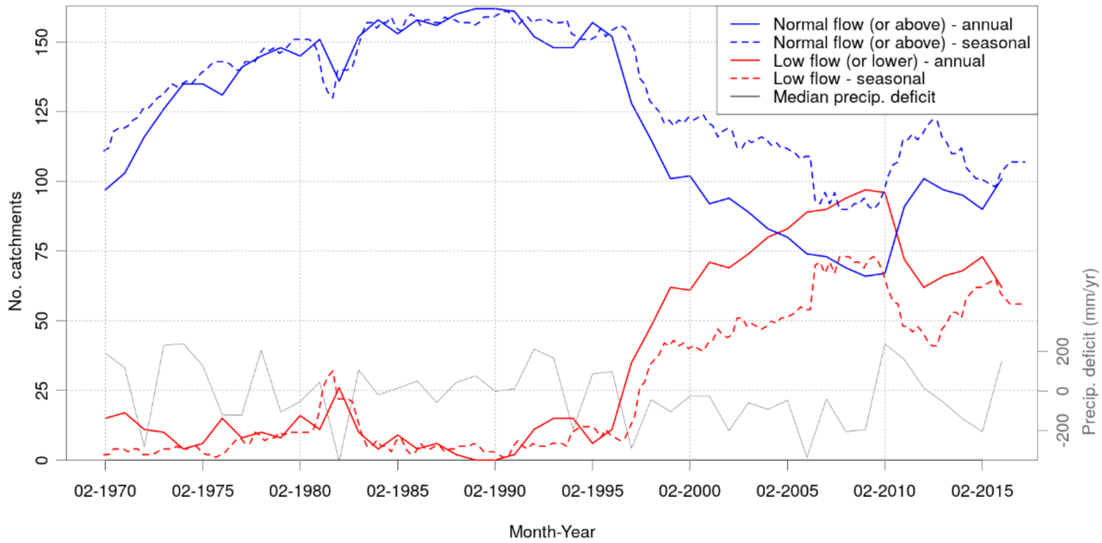

Figure 1. Runoff state estimation of 162 unregulated Victorian catchments. Plot shows results from annual and seasonal timestep Hidden Markov Modelling. The annual precipitation deficit is the median from the 162 study catchments.

Keywords: *Hydrological resilience, Hidden Markov Modelling, time-series analysis, rainfall-runoff*

Assessment of hydrological stationarity of the Border Rivers catchment

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Abstract: WaterNSW is currently developing the water resources planning models for all regulated NSW valleys including the Border Rivers Valley (BRV), where WaterNSW has responsibility for bulk water supply. The planning models will enable WaterNSW to assess the level of services and undertake the assessment of future water resources infrastructure options. The planning model requires long-term catchment inflows, which are available but for shorter durations. For this reason, the calibrated catchment rainfall-runoff model is used to calculate long-term inflows based on available long-term rainfall and evaporation data.

Recent studies and relevant data show that Border Rivers catchment has undergone the significant land use changes in the recent time, particularly, in the second half of the 20th Century. As a result, the runoff characteristics of the catchments are likely to change in these years. As the part of the model calibration, this paper investigates the hydrological stationarity of the catchments over the period ranging from 1970 to date, where the observed flow data are available for selected catchments. For this study, four unregulated catchments have been considered with insignificant abstraction. The daily Sacramento rainfall-runoff model was developed for each catchment.

To assess the catchment stationarity, the simulation period has arbitrarily been divided into two parts: pre-1992 (1975 to 1991) and post-1992 (1992 to 2016). The catchment rainfall-runoff models are calibrated over the pre-1992 period and validated against the post-1992 flow data and vice-versa. The simulation results clearly show that the catchment runoff characteristics have changed over the time. The runoff has, in general, decreased over the catchment in recent years, and the decrease in runoff appears to be significant and consistent across the catchment. The whole exercise was repeated with catchment rainfall and Morton Wet Environment Evaporation data from SILO database. The results still hold. Since it has been assumed that the rainfall and potential evaporation data used for rainfall-runoff simulation are stationary, the authors believe that the potential reasons for the non-stationarity in the runoff are the following but not limited to:

- Changes in land use in the catchment in recent time,
- Increases in the on-farm storage in the catchment, and
- Increases in the unregulated abstraction in the catchment in the recent time.

More detailed works will be required to ascertain the cause for catchment non-stationarity with greater confidence. Based on the outcomes of this analysis, WaterNSW has used the recent (post-1992) data for the calibration of the rainfall-runoff model for the Border Rivers to estimate the catchment inflows, which have been used for the development of the planning model.

Keywords: *Border Rivers, rainfall-runoff, non-stationarity, calibration, validation*

How might climate change impact conceptual hydrologic models? An ecohydrologic experiment

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Abstract: When assessing hydrologic model robustness to climate change, it is common to test performance under contrasting historical periods. For example, a model calibrated under wet conditions may be tested under increasingly dry conditions. The decreasing performance as the testing conditions deviate further from the calibration conditions is taken as indicative of likely performance degradation under climate change scenarios with comparable rainfall decreases. There are many studies that inherently apply the assumption that past variability can be used as a proxy for future climate change, but the analogy may be flawed for three reasons:

1. Due to lagged responses to climate shifts, catchment behaviour under long-term wetting or drying may not be fully represented over short-term wet or dry periods.
2. Distinct subsets of the past record defined based on rainfall are unlikely to reflect the temperature increases we expect in the future
3. Past observations do not reflect the increases in carbon dioxide concentrations associated with climate change scenarios

If any of these three factors substantially impacts catchment response, subsets of the historical record will not be accurate proxies for future climate. We tested each assumption using the ecohydrologic model RHESSys that dynamically simulates vegetation growth, subsurface flow and nutrient cycling. We found that all three assumptions were relevant in determining possible catchment response to altered climate conditions, especially for drier future scenarios. For our study catchment, persistence of dry conditions over many decades led to different subsurface flow conditions than the same conditions experienced over shorter timeframes, leading to different catchment response. This means that long-term climate change effects will not be represented over short historical periods. The impacts of increased temperature and carbon dioxide concentrations on vegetation (which are not accounted for in past observations) further altered runoff behavior. We estimate that by ignoring persistence in rainfall changes, temperature increases and carbon dioxide levels, researchers could underestimate performance degradation in terms of Nash-Sutcliffe efficiency by as much as 0.41. This implies that the use of past periods to test model performance under climate variability will not give a reliable indication of robustness to long-term climate change. The uncertainty introduced in hydrologic modelling by future climate change has probably been underestimated in the current literature.

Keywords: *Climate change, model robustness, ecohydrologic modelling, catchment response*

Robust parameterisation of rainfall-runoff models for climate change impact assessment

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Abstract: There are many rainfall-runoff and hydrological models in the literature, developed for various applications including predicting streamflow response to changes in climate inputs and land use characteristics. These models use different structures and methods to conceptualise the landscape hydrological processes, use rainfall and climate time series as input data, and are generally calibrated and tested against observed streamflow data. Practically all climate change impact on runoff studies use future climate series informed by projections from climate models to drive a hydrological model developed and calibrated against past hydroclimate data (Chiew et al. 2009, 2017). In modelling the future runoff and hydrological characteristics, most studies use parameter values from model calibration against the entire length of available observed historical dataset to encapsulate the large range of hydrological conditions. However, interpreting results from these simulations will become more challenging as we extrapolate the hydrological models to predict further into the future where hydrological fluxes and stores will be influenced not only by the changed climate input data, but increasingly by higher temperature, dominant hydrological processes under longer dry spells, and ecohydrological processes under higher CO_2 not seen in the past (Chiew et al. 2014).

Several studies have now shown that traditional application of hydrological models will underestimate the range in the projected future hydrological impact, that is, it will underestimate the decline in runoff where a runoff decrease is projected, and underestimate the increase in runoff where a runoff increase is projected (Vaze et al. 2010, Saft et al. 2016). This paper builds on the research of Fowler et al. (2016, 2018) to explore a more robust calibration of rainfall-runoff models for climate change impact study. Specifically, the models are calibrated to produce good calibration metrics (mainly NSE) in the driest and wettest 10-year periods (rather than the best calibration over the entire calibration period), and at the same time reproducing the total observed streamflow within five percent over the entire calibration period. The range in the modelled future runoff from this robust calibration are then compared with the modelled future runoff from the traditional calibration. This study is funded by the Victorian Water and Climate Initiative and uses data from 30 catchments across Victoria which experienced the 1997–2009 Millennium drought. Results from the modelling shows that this robust model calibration can produce a more accurate estimate of the uncertainty in the projected future runoff, but cannot entirely eliminate the modelling limitation of underestimating the projected range in future runoff.

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Acknowledgement

This research is funded by the Victorian Water and Climate Initiative.

Keywords: *Climate change, runoff, projection, rainfall-runoff modelling, robust calibration*

Projections of water futures for Australia: an update

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Abstract: This paper presents projections of hydrological metrics for Australia under a future climate, from modelling carried out in the Earth Systems and Climate Change Hub. These projections are modelled using three rainfall-runoff models informed by future climate projections from 42 CMIP GCMs used in IPCC AR5. The runoff projections are the same as those presented in Chiew et al. (2017). The paper also presents projections of hydrological metrics beyond just the long-term averages that are important for many applications. The paper presents and discusses the implications of different data treatments used to obtain future climate series to drive hydrological models, modelling with different hydrological models, and limitations and challenges in modelling climate change impact on hydrology. Future runoff is likely to decline in far south-west and south-east Australia, but the range or uncertainty in the projections is large. Despite continuing progress in climate change and hydrological modelling sciences, the uncertainty in projections is likely to remain large. Planning water systems and outcomes for the future need to consider the range of plausible climate and water futures, and develop adaptation options that balance the cost of adaptation versus the risk from not adapting sufficiently and fast enough.

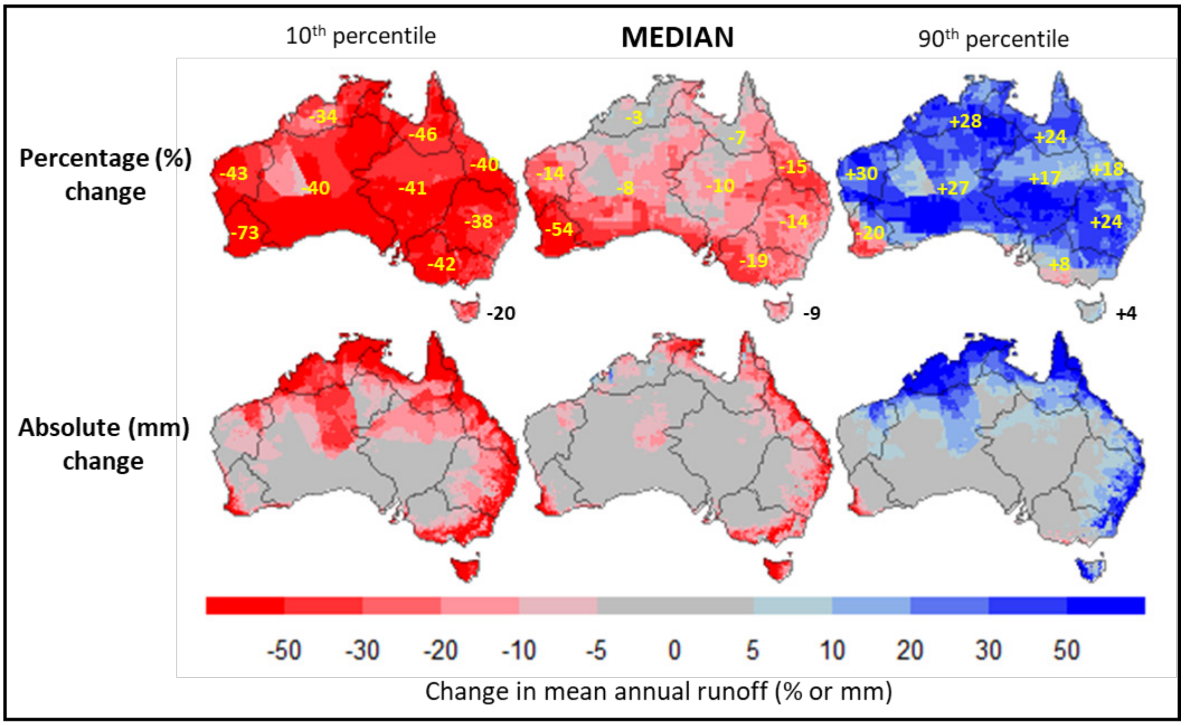

Figure 1. Projected change in mean annual runoff (median and the 10th and 90th percentile values from GR4J hydrological modelling informed by climate change projections from the 42 CMIP5 GCMs) for RCP8.5 for 2046–2075 relative to 1976–2005. The projections also reflect change in runoff for a ~2.2°C global average warming relative to the 1986–2005 IPCC AR5 reference period. The large range in the projections mainly reflects the uncertainty in rainfall projections across the 42 CMIP5 GCMs.

***Keywords**: Climate change, runoff, projections, water futures, hydrological metrics, Australia*

Downscaling runoff products using areal interpolation: a combined pycnophylactic-dasymetric method

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Abstract: Hydrological models are commonly forced with variables describing climate. These variables are often obtained from climate models, requiring processing via interpolation or downscaling in order to be useful for the hydrological modelling study. Outputs from climate – as well as hydrological – models are generally expressed as spatially explicit fields, but the results from hydrological models are rarely interpolated or downscaled. There can be many reasons for this. For instance, the existing model output may be of incompatible spatial units (raster, when vector needed, or vice versa), or of a different scale (regional, where local scale is needed). Runoff generation is a local process which is determined by the influx of water, landuse, vegetation and soil characteristics, and there have been many applications of its interpolation to watersheds, river lines or as continuous fields. However, most of the methods employed in runoff interpolation are statistical and do not account for process characteristics in runoff generation in the interpolation step.

Here we present a novel spatial interpolation method for the purpose of downscaling coarse resolution runoff products based on areal interpolation. Areal interpolation is a process where a variable from a source zone is reallocated to overlapping target zones. We combine two advanced methods: Dasymetric Mapping (DM), which is simple Area weighted Interpolation (AI) informed by an ancillary variable, and Pycnophylactic Interpolation (PP), which is designed to refine the spatial distribution of a variable within the source zone. Each of these methods preserve mass balance – the volume of runoff from source zone is preserved in the target zones. Our methodology can address the Modifiable Area Unit Problem (MAUP) – a statistical bias caused by the sensitivity of analytical results of spatial data to levels of aggregation (the scale effect), as well as the arbitrary sizes, shapes, and arrangements of zones (the zoning effect). Addressing MAUP enhances usability of existing model results for runoff estimation because the zoning can be modified to fit the needs of a new analysis. The method is also able to take into account the spatial distribution of characteristics which govern runoff generation in the interpolation step.

To test the methodology, we downscale a coarse global runoff product, LORA (Linear Optimal Runoff Aggregate), on to 126 Australian catchments with natural flow regimes, and compare how AI, DM, PP and the combined PP-DM fare against streamflow records. A recently developed topographical index, DUNE (Dissipation Per Unit Length), which is able to distinguish topographies with different runoff regimes, is used as the ancillary variable in DM and PP-DM. We assume that runoff is highly correlated with precipitation and we assume it can be interpolated with a smooth function. We also assume that topography can inform us about the actual distribution of runoff generation within a source zone (the spatial unit in a runoff product).

We find that the simple AI method is more efficient in replicating the runoff profile in arid catchments where potential evapotranspiration is higher than precipitation. However, as precipitation increases and aridity is reduced, DM and PP-DM prove more efficient in replicating the recorded runoff. Using DUNE as the ancillary variable also results in higher performance in catchments with variable topography and performs worse in less variable terrain. In catchments with a high range of slopes, DM and PP-DM utilizing DUNE are consistently better than AI or PP, which do not utilize DUNE. Additionally, we find that in wet catchments which are located entirely within a single source zone of runoff, the performance is higher using DM, PP, and PP-DM than with the simple AI. In catchments which are covered by multiple source zones there is no clear benefit in using the more advanced areal interpolation methods over AI.

Our results show that the method is able capture the spatial variability of runoff generation, but this requires careful selection of the ancillary variable or a combination of ancillary variables. It is also evident from the results that arid and wet catchments require a different approach in runoff downscaling. Further investigation with a larger sample is needed to fully understand the properties of the downscaling methods.

Keywords: *Downscaling, runoff, global hydrology, interpolation*

Updated AWRA-L input spatial layers at ~1 km and ~5 km resolutions for the Australian continent

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Abstract: The Australian Water Resources Assessment landscape and groundwater (AWRA-L) model is one of the main components of the modelling system used by CSIRO and the Bureau of Meteorology (BoM) to assess and account water resources across continental Australia. The model is continuously being developed by CSIRO to address the needs of its users and stakeholders. In 2016-2017, the BoM and CSIRO implemented the model at a finer spatial resolution of 0.01° (~1 km) instead of its original spatial resolution of 0.05° (~5 km). The number of hydrological response units (HRUs) was also increased from two (for shallow-rooted and deep-rooted vegetation) to five (including HRUs for large water bodies, irrigated agriculture, and impervious areas). The improvements were implemented using the Murrumbidgee River Basin as a test basin. The results show that with the incorporation of the five HRUs, the model can now explicitly simulate the hydrological processes in impervious areas, large water bodies, and irrigated agricultural areas. With the implementation of the model at a finer spatial resolution and depiction of the five HRUs, the model showed improvements in providing water balance estimates for the test basin. The improved model may now be implemented in other catchments within Australia, provided that the required spatial data inputs for the area are available.

In this study, we have regenerated all the AWRA-L spatial layers for five HRUs both at 0.05° (~5 km) and 0.01° (~1 km) for the Australian continent. We have derived the spatial data layers for the entire continent using the most recent data to ensure the reliability and consistency of the spatial layer inputs. We have generated a total of 48 spatial layers, excluding the climatological inputs. Figure 1 shows an example of the five layers generated at 0.01° (~1 km) to depict the five HRUs. The climatological inputs from 1970-2012 have also been updated to match with the spatial grids of the AWRA-L model. The updated input spatial layers are essential for implementing the improved AWRA-L model at any catchment and local scale within continental Australia. Catchments with a high fraction of impervious areas, large water bodies, or irrigated agricultural areas will benefit the most from these updates.

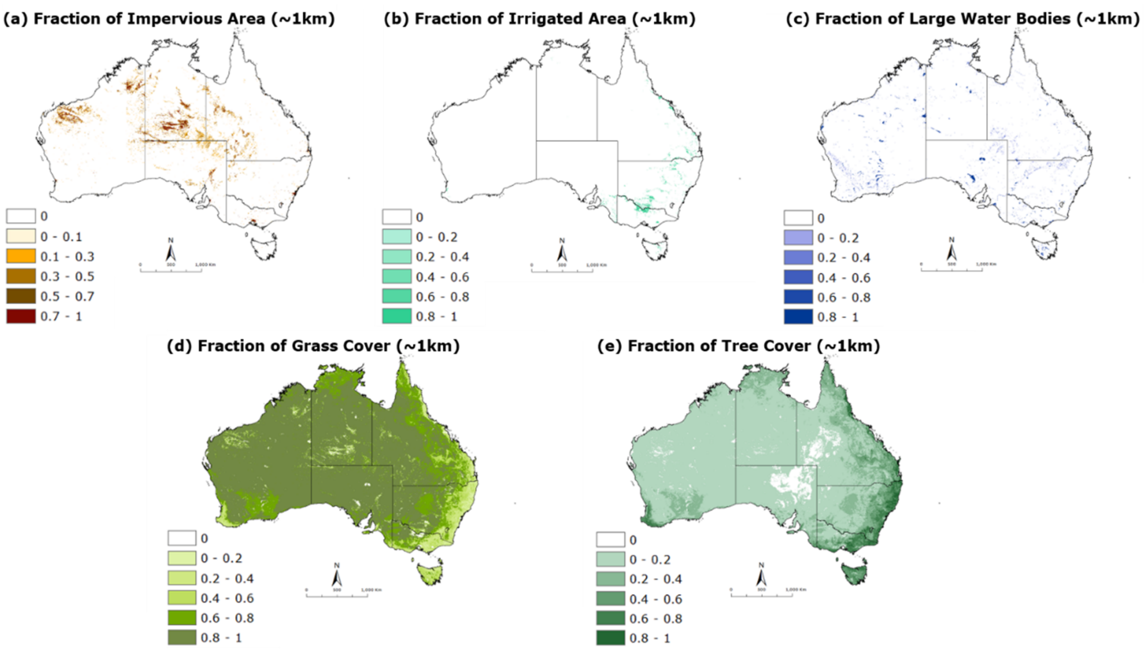

Figure 1. Spatial input layers at 0.01° (~1 km) spatial resolution showing the fraction of (a) impervious area, (b) irrigated agricultural area, (c) large water bodies, (d) shallow-rooted vegetation, (e) deep-rooted vegetation

Ref: Vaze, J.; Mateo, C.; Wang, B.; Teng, J.; Marvanek, S. AWRA-L input spatial layers at ~1 km and ~5 km resolutions for the Australian continent - Source data and comparison between 1 km and 5 km resolutions. Australia: CSIRO; 2018. https://doi.org/10.4225/08/5b182f36b6fec

Keywords: *AWRA-L spatial data, hydrological modelling, fine resolution modelling*

Exposing underlying hydrological processes and using them for regionalization of large-scale hydrological models

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Abstract: When implementing large-scale hydrological models, the principal parameter estimation problem is that of ungauged watersheds. Model parameters for these watersheds cannot be calibrated and need to be estimated by other methods. Regionalization is defined as the transfer of information, as calibrated parameters, between watersheds that are considered to be hydrologically similar. In this work, we use Partial Least Squares Regression Analysis (PLSR) to expose the hydrological processes behind the hydrology of the region under study. These are then used as similarity metric to identify hydrologically similar watersheds.

PLSR is a statistical method used to expose relationships between defined sets of independent (*X*) and dependent (*Y*) variables. In our approach, *X* is the set of watershed characteristics that are known for all watersheds; and *Y* is a set of discharge metrics. Discharge metrics can cover all, or specific flow conditions depending on the project objectives. PLSR transforms *X* to a reduced dimension of latent variables. The identified latent variables indicate the relative importance of the different watershed characteristics in explaining the hydrological responses considered, and are the base to infer the importance of the different hydrological processes behind the hydrology of the region under study. Not only the latent variables provide insight into the fundamental hydrological processes, but also, they provide an objective similarity measure to be used for regionalization in large-scale hydrological models.

Regionalization using latent variables follows this procedure: PLSR analysis is performed using all gauged spatially distinct watersheds in the region under study, where both independent and dependent variables are known. The latent variables for the region, corresponding to the discharge metrics considered, are identified and, because they are linearly related to known watershed characteristics, they can be calculated for all watersheds in the study area (gauged and ungauged). Hence, every watershed in the study area can be represented as a point in the latent variable space and their proximity is used to identify hydrologically similar watersheds.

This regionalization approach was applied to the hydrological model of a region of 736,780 km^2 in Western Europe. 698 monitoring points were available for modelling. 462 were used for PLSR analysis and from these, 246 head watersheds, covering 10% of the modelled area, were individually calibrated using the SWAT model. Latent variables were calculated for all watersheds in the study area. Each ungauged watershed was assigned to the most similar calibrated watershed (the closest in the latent variables space), and received its calibrated parameters. Simulations results were assessed in monitoring points not used for calibration. Results of PLSR analysis indicate that typically available watershed characteristics explain fairly well average conditions, but poorly extremes. Nonetheless, simulation results with regionalized calibrated parameters considerably improved throughout the modelled area compared to initial conditions, especially for error and bias measurements. Further, this regionalization approach demonstrated the efficient use of available data; improved results were achieved by only calibrating 10% of the modelled area; and regionalized parameters resulted in a variety of parameter sets, better addressing the variety of hydrological conditions existing in large-scale applications.

Keywords: *Large-scale hydrological modelling, PLSR analysis, regionalization, similarity, ungauged watersheds*

A multi-scenario Decision Support System for real-time operation of over-year multi-reservoir systems 1. Model structure

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Abstract: Water resources systems for water supply with over-year behaviour are widespread in many areas of the world, including Southern Europe, Middle East, China, Western US, South Africa and Australia. Although in these systems the risk of highly variable inflows is partially internalized in the design process by letting these reservoirs have large storage capacities, operation of these systems is challenged by changing demand levels, changing purposes and objectives, and climate change. Given their dimensions, these systems are often managed in a centralized fashion, with one authority planning allocations to different users. As inadequate management may operate the system either too conservatively or in a fashion unaware of the occurrence of long, multi-year dry spells, the decision-making process should be supported by appropriate decision support tools. When used on a regular basis, in a real-time mode, by updating current information on water resources status and using inflow forecasts, such support tools should be able to identify risky situations suitably in advance, suggest appropriate hedging policies and optimize the use of additional, costly, water resources that can help mitigate the impacts of sustained dry periods.

One of the key factors for a successful management is obviously the ability to predict future inflows into the system suitably in advance. Presently, the state of the art of climate services is provided by seasonal climate forecasts over a six-month horizon, coupled with downscaling models to turn climate input into streamflow. Forecasts for further-reaching time periods are an active field of research, but are not currently used by industry. However, also downscaled seasonal forecasts are out of reach for most water agencies and utilities, as they imply the availability of ad-hoc skills, resources and facilities to acquire climate forecasts and turn them into inflow forecasts. It hence makes sense to develop simpler, data-driven forecast systems to be integrated into the decision support tools to improve the quality of decisions, while research progresses, and resources and skills for implementing hydrological forecast are being developed

To this end, in this paper we introduce a multi-scenario mathematical programming (algebraic) model for real time management of a multi-reservoir system for water supply where consideration of a multi-year Forecasting Horizon (FH) is necessary given the physical features of the system. It is a linearized MIP (mixed integer programming) model that optimizes water allocations to municipal and irrigation demand centres driven by the objective of minimizing weighted total discounted costs (scarcity costs plus costs of additional water resources) along the multi-year FH, being the weights the occurrence probability of each of the three inflow scenarios. Constraints include 1) mass balances at system's nodes, 2) systems' topology, 3) component's capacity, 4) spills, 5) non-empty conditions on reservoir storage at the end of the FH. It is a multi-scenario optimization tool because future, uncertain inflows are modelled, until the end of the current water year, as three different inflow scenarios: low flows, normal flows and high flows. The optimization model is solved for the three different scenarios and a unique solution that can be turned into one actual, implementable decision at the present time step is obtained by imposing non-anticipatory (or congruity) constraints according to the principle of scenario aggregation. Given the over-year nature of the systems of interest for this study, the time unit is one month.

This paper is devoted to the description of the structure of the DSS, of the procedures followed to estimate scarcity costs and of the techniques used to linearize this partly non-linear model. Construction and estimation of scenarios as well as results of DSS simulation to evaluate its performances are the object of a companion paper.

Keywords: *Decision Support Systems, real time reservoir system management, scenario optimization*

A multi-scenario Decision Support System for real-time operation of over-year multi-reservoir systems 2. DSS simulation

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Abstract: A companion paper (Arena et al, 2019) has introduced the architecture of the DSS and has described its governing equations. In a real-time, dynamic decision-making context, it is a tool to support decisions at the current time step concerning water allocations to municipal demand centres and irrigation districts as well as additional intakes from costly water sources in a water resources system featuring reservoirs with over-year behaviour. The DSS is designed as a linearized MIP (mixed integer programming) optimization model and as such, it includes an objective function and constraints on 1) mass balances at system's nodes, 2) systems' topology, 3) component's capacity, 4) spills, as well as non-empty conditions on reservoir storage at the end of the Forecasting Horizon (FH). It is a multi-scenario optimization tool because future, uncertain inflows are modelled, until the end of the current water year, as three different inflow scenarios: low flows, normal flows and high flows. The optimization model is solved for the three different scenarios and a unique solution that can be turned into one actual, implementable, decision at the present time step is obtained by imposing non-anticipatory (or congruity) constraints according to the principle of scenario aggregation (Rockfellar and Wets, 1987). The objective function is the weighted sum of the scarcity costs at all demand centres and of cost of water supply from additional sources along the multi-year FH, discounted to their present value, being the weights the occurrence probability of each of the three inflow scenarios. Given the over-year nature of the systems of interest for this study, the time unit is one month.

This paper first discusses estimation of scenario probabilities and of scenario inflows, then describes the application of the DSS to a real-world, two-reservoir system in Southern Italy. Its performances, in terms of scarcity costs and costs of additional, costly, water resources, are simulated over a forty-year historical period, on a monthly basis. Sensitivity of the DSS to different demand levels is explored considering different drift scenarios. Furthermore, in order to contrast the performances of the multi-scenario DSS presented here (DSS-SC), we introduce a single-scenario DSS, identical to the multi-scenario one, except that decisions are made based on exogenous inflow forecast vectors. We look at two different types of forecast vectors that are meant to provide a lower and upper bound of DSS performances: the first type is a vector containing only the long-term means of monthly inflows and gives rise to DSS-WF (where WF stands for "worst forecast"). The second vector type contains instead real (i.e. actually occurred) inflows in the first six months of the FH and long-term means of monthly inflows for the remaining FH – 6 months. It gives rise to a DSS-BF (BF stands for "best forecasts").

Results show that DSS-SC compares quite favourably with DSS-BF: differences in total costs range from 37% for drift=0.75 to 27% for drift = 0.5. DSS-BF clearly outperforms DSS-WF with improvements ranging from 17% (drift = 0.75) to 62% (drift = 0.90). In one demand condition, described by a drift of 0.9, DSS-SC even outperforms DSS-BF. Investigation of this behaviour led to recognize that, at least for this drift, DSS-SC would manage the system so to keep the largest reservoir of the system full enough to allow issuing less restrictive irrigation supply reductions than its DSS-BF counterpart, and would therefore reduce the associated scarcity costs. This thought-provoking situation, if on the one hand confirms that in these long-memory systems "abrupt" failures can be the consequence of long-term policies and decision styles, on the other hand stimulates the reflection that DSS performances can indeed depend on a number of different factors that need to be investigated in deeper detail. From this standpoint, a single historic time series is probably not enough to explore the different possible behaviours of the DSS. For this reason, a stochastic validation of DSS-SC, by simulating its behaviour through synthetic time series, is in order and is the next research objective.

Keywords: *Decision Support Systems, real time reservoir management, scenario optimization*

Two approaches that address challenges in integrating optimisation into water supply planning

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Abstract: Melbourne Water harvests, treats and supplies water to Melbourne and surrounding regions. The supply system includes 10 surface water storage reservoirs, a desalinated water plant, and 1,067 kilometres of water mains. Management of this system is informed by a range of planning processes and outlooks over the short-term (1-3 years) and long-term (15-50 years). Similar management objectives exist for both planning timeframes, including maximising water security outcomes whilst minimising operational and/or capital cost. The two planning timeframes are distinguished by different levels of certainty and provide different insights for decision-making. Short-term planning focuses on providing near-term water security through management decisions such as utilisation of surface water and volumes sourced from the desalinated water plant. Long-term planning informs the timing of augmentation of supply and demand management measures, and provides outlooks of the follow-on impacts of short-term decisions.

The combination of uncertainty in forecast climate and demand and number of possible planning decisions means that planning is supported by numerous scenario-based assessments. These assessments are typically achieved using a simulation model of the water supply system. However, as the number of possible decision sets increases, linking optimisation techniques to the simulation model becomes an effective tool for exploring a wider range of possible decisions and finding those that best meet management objectives. Due to the trade-offs inherent between objectives of maximising water security and minimising cost, optimisation using such objectives results in a large number of optimal decision sets representing different compromise solutions. This presents a challenge in interpreting the information and incorporating it into planning processes.

Whilst visualisation techniques have been a useful tool for planners to better understand multi-objective trade-offs, it has remained challenging to present these to non-technical audiences or to summarise the outcomes for decision-making. This can be circumvented by evaluating the optimal decision sets against multiple criteria representing the management objectives, and using weighting or preference ranking to select a single or reduced set of preferred decision options for implementation. With this in mind, we developed enhancements to two of our existing scenario-based model analyses for short and long-term planning to integrate optimisation techniques. These enhanced methods differed between the short and long-term as was required to suit the number of decisions and the level of certainty in outcomes. However both methods involved evaluating or optimising decisions in the form of potential volumes of water sourced from the desalination plant, assessing these decision outcomes against a set of existing water supply planning criteria, and using preference ranking to select and present candidate decision sets that best perform against the criteria. The information presented from this assessment was readily understood and gave us a clearer and more confident picture (than a scenario-based approach) of our ability to adapt to future conditions to best meet the management objectives. These enhanced methods provide an example of how optimisation techniques can be readily integrated into water supply planning to improve robustness of decision support information.

Keywords: *Water resource management, optimisation, water supply planning*

Irrigation water resource management: 'IW-QC2' software tool

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Abstract: It is well recognized that current practices and sustainable expansion of horticulture in the Northern Adelaide Corridor region (including the Northern Adelaide Plains, NAP), South Australia are strongly influenced by the availability of reliable water resources of suitable quality for the range of crops grown in horticulture practice. Further considerations are the type and condition of soils for soil-based enterprises and the range of climatic conditions expected in the region, including extreme events, of short and long-term duration.

Irrigation practices within covered (greenhouse) horticulture industries vary depending on a range of factors including crop type grown, crop evapotranspiration (ETc) rate, being soil-based or hydroponic, ambient temperatures and water supply quality, e.g. salinity. From a landholder survey conducted in 2018 to determine water management in soil-based horticulture practices of the NAP, it was found that ambient temperature-based irrigation schedules are applied for soil-based open horticultural practices and additional irrigation is applied to leach of salts from the soil profile. For the hydroponics industry of the NAP, decentralized reverse osmosis treatment is used to desalinate groundwater and brackish recycled water.

In this paper, we describe a tool design to enable rapid determination of the quantity and quality of irrigation water produced through blending of different water sources. These sources include harvested stormwater, recycled water, local surface streamflow and ground waters. This tool is currently for soil-based greenhouse crops (i.e. tomato, cucumber, capsicum and eggplant) commonly grown in the NAP region but can be readily modified to include other covered crops. The modelled surface water supply (volumes and quality) can be calculated from historical climate data or future climate predictions. Model options include prediction of water harvested from greenhouse roofs (with user selected climate models) used when initially available (during the wet season) or stored and used to blend with other water sources to achieve fit-for purpose water qualities specific for crop type and growth stages.

To model these scenarios, a software tool (in Microsoft Excel) termed 'Irrigation water quality and quantity for covered crops' (or 'IW-QC2') was developed. This is for application by water resource managers and the horticulture industry to facilitate decision-making on water resource selection, water storage capacities and quality of blended supply water, with user selected climate model. IW-QC2 output includes determination of the amount and quality of irrigation blended waters for soil-based crops and when desalination (reverse osmosis, RO) is required, based on the trigger values for TDS and chloride concentrations for irrigation water for specific crops.

Keywords: *Greenhouse, irrigation, water resources, climate prediction*

*fore*SIGHT - An R package to support scenario-neutral climate impact assessments

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Abstract: There is a growing appetite for scenario-neutral approaches that 'stress test' a system's performance against a range of plausible hydroclimate scenarios. This 'stress testing' allows for system sensitivities and failure modes to be uncovered irrespective of climate projections. However, there are substantial technical challenges in effectively stress testing a system using scenario-neutral approaches due to: (i) the requirement for the generation of suitable sets of hydroclimate time series (scenarios) to effectively explore system sensitivities, (ii) the computational and logistical overheads in simulating system performance in response to large sets of hydroclimate scenarios, and (iii) the need to visualize system performance across the range of scenarios such that system sensitivities and modes of failure can be uncovered.

*fore*SIGHT (Systems Insights from Generation of Hydroclimatic Timeseries), an R package for conducting climate impact assessments, was developed in answer to these challenges and to encourage the wider adoption of scenario-neutral approaches. The R package is able to generate perturbed daily time series for a range of hydroclimate variables (e.g. temperature, precipitation, radiation and potential evapotranspiration) using multiple approaches including: (i) the stochastic simulation of perturbed time series via an inverse approach, and (ii) the simple scaling of observed time series. The package utilizes formal optimization techniques with the stochastic models to create desired time series which, importantly, enables the perturbation of a variety of different hydroclimate variable characteristics (e.g. persistence, means and percentiles) thereby allowing for greater exploration of system sensitivity. *fore*SIGHT allows for the integration of system models both internally in R and externally so that 'stress testing' can be seamless and incorporates a range of options for visualization. Stepwise tutorials are provided that walk the user through using the software for scenario-neutral climate impact analysis.

Keywords: *Climate change impact assessment, scenario-neutral, bottom-up, inverse approach, stochastic rainfall*

Understanding large-scale streamflow trends in the southern Murray Darling Basin

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Abstract: Understanding long-term trends in streamflow is important to support water resources management for freshwater basins all over the world. In Australia, a key region for understanding streamflow trends is the Murray Darling Basin (MDB) due to its significant role in water resources. However, there is still a lack of comprehensive understanding of streamflow trends in this region, particularly trend magnitudes, which has limited the value of existing trend estimates on informing decision-making for catchment management authorities and water utilities. Furthermore, current studies have limited understanding in the regional patterns of streamflow trends in the MDB. To address this, we used an integrated trend investigation approach to examine long-term streamflow trends at 51 gauging stations in the southern MDB.

We used two approaches to investigate trends at both the individual station and regional levels. Innovative Trend Tests (ITT) was first conducted for individual sites, aiming to estimate trend magnitudes at individual stations. This method provides effective estimates of site-level trends, without the need for data transformation and pre-whitening, which are often required for streamflow data due to high skewness and autocorrelation. Bayesian hierarchical model (BHM) was applied to explore streamflow trends at a region-level, as well as for identifying impacts of the key controls of spatial variation in these trends. The key strength of BHM is the ability to incorporate regional information to overcome variability in record lengths across gauging stations, and thus provide reliable regional-level trend estimates. To inform the BHM structure, we developed multi-variate regression models to relate spatial variation in the estimated trends from ITT with a large number of catchment characteristics such as climate, land use, geology and vegetation, from which the most important drivers were identified.

We found a consistent long-term decreasing trend in streamflow over the observed period in the southern MDB: -5.5% ~ 0% per year from the site-based trend analysis and -3% ~ 0% per year from the regional trend analysis. Figure 1 shows the regional trend results from BHM. We concluded that spatial variability in streamflow trends can be best explained by differences in average climatic conditions across these sites. Results of this study can be used to inform the development of basin plans and strategies to ensure sustainable water supply. The trend investigation approaches used in this study are transferable to other basins for assessing trends for large spatial extents and over different time periods, and thus to provide valuable insights into water resources management and decision-making challenges around the world.

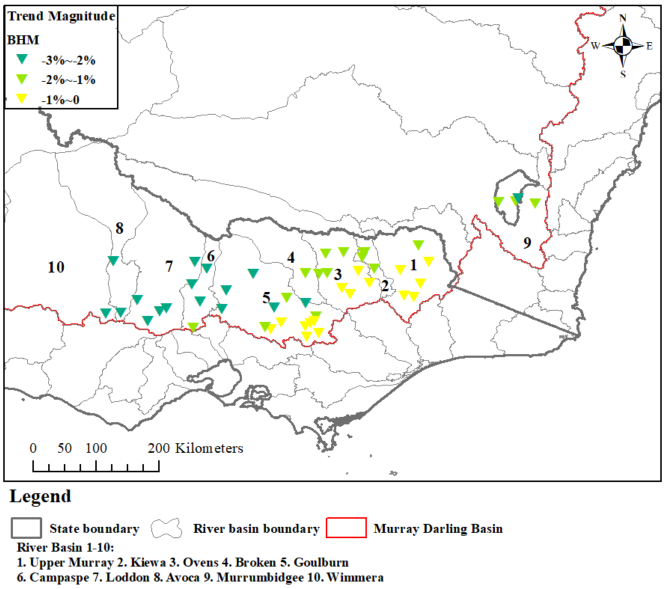

Figure 1. Regional trend analysis results from Bayesian Hierarchical Model (BHM)

Keywords: *Long-term trend, streamflow, Innovative Trend Test, Bayesian Hierarchical Model, Murray Darling Basin*

Soil water modelling for irrigation scheduling: how well can we do with limited data?

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Abstract: Irrigation water is an expensive and limited resource. With effective irrigation scheduling, we can save irrigation water while improving crop productivity. A key aspect of irrigation scheduling is accurate estimation of crop water use and soil water status. This requires extensive input data that are often not available. This study aims to provide a large-scale evaluation of our ability to estimate soil water in data-scarce situations, and thus prioritize future needs for better monitoring and modelling.

The study focuses on one of the most important Australian irrigation districts, the Goulburn-Broken region. We consider 11 flood-irrigated farm paddocks which span a range of key crops in the region that includes pasture, maize and Lucerne. At each paddock, the only in-situ measurements available are rainfall and soil moisture. Soil water balance is calculated using a simple bucket model at individual paddocks for the corresponding root zone depths informed by crop type and soil water variation. We focus on drying periods between irrigation applications due to potentially high uncertainties in the estimates of irrigation depth. Additional input data are sourced from the public domain and literature, including: soil properties are extracted from the Australian Soil Resource Information System (ASRIS), which define the size of the bucket; to calculate crop evapotranspiration, we obtained climatic data (air temperature, solar radiation, wind, humidity) from weather stations maintained by the Australian Bureau of Meteorology, together with crop factor information obtained from the Food and Agriculture Organisation (FAO). The rate of soil water depletion (i.e. plant water uptake) is represented by 1) crop potential evapotranspiration, for a non-water-stress situation; and 2) a linear function between crop potential evapotranspiration and zero, depending on crop water stress. We then evaluate the modelled soil water against ground measurements to understand how model uncertainties vary with space, time, soil water conditions, and other potential factors.

Future works are required to calibrate the ground measurements to improve the uncertainty estimation. However, our key results so far suggest that: 1) model can reproduce in-situ soil moisture contents reasonably well in most locations where no drainage occurred, and when crop water uptake was not limited (i.e. non-stressed); 2) in contrast, where drainage and water stress were presented, the model exhibits high uncertainty due to uncertainties in the bucket size i.e., field capacity and wilting point; 3) rooting depth also has a critical role in accurate representation of the soil water depletion rate. These highlight the importance of accurate definition of soil properties for modelling soil water, which prompt further improvement in the monitoring and investigation of soil conditions. This approach is transferable to other irrigation regions where data are scarce, for identifying effective modelling approaches and thus better informing irrigation scheduling.

Keywords: *Irrigation scheduling, soil water modelling, field capacity, wilting point, crop evapotranspiration*

The merits of transient stochastic climate change projections for risk assessments of water resources

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Abstract: Assessments of climate change risks to water resources have largely been driven by climate change projections often by providing snapshots of climate conditions in future periods. Water resource managers are, however, required to plan for infrastructure and operations over different time horizons, which creates a demand for climate change projections that reflect changes in climate over time, known as transient climate time series. Global and regional climate models produce projections of transient climate change in response to various scenarios of greenhouse gas emissions. However, computational capacity limitations restrict the ability to run the models with sufficient repetition to adequately sample the uncertainty resulting from internal climate variability [Deser *et al.*, 2012] that are necessary for adequate risk assessments of water resource systems [García *et al.*, 2014] as they exhibit non-monotonic performance responses to climate [Kjeldsen and Rosbjerg, 2004]. Stochastic weather generators where climate parameters may be adjusted conditional on time provide an avenue for assessing water resource systems in a manner that address both uncertainties with respect to internal climate variability as well as changes imposed by climate change.

We use a conceptual reservoir model to assess reservoir performance and drought risk over time under climate change and compare the performance in response to both step changes and transient changes in climate. Projections of climate are sourced from the NARCliM project [Evans *et al.*, 2014]. These outputs are from a regional climate model that downscales projections from four selected CMIP3 GCMs with the precipitation outputs bias corrected to reflect daily rainfall frequencies and magnitudes. We find that the utility of a water resource climate risk assessment driven by climate change projections is limited by:

- cascading uncertainties associated with using hydrological data derived from using a succession of global climate, regional climate, catchment, and system models; and
- the probabilistic nature of risk assessments that is incompatible with scenario driven climate projection experiments as all scenarios are plausible and are not probabilistic.

In addition to these general limitations our assessment was only able to consider climate projections from the small number of GCMs that were used in the NARCliM project. We therefore performed an additional assessment of the reservoir risks imposed by climate using the decision scaling approach, which is one of a family of robustness-based approaches to climate risk assessments. The decision scaling framework is characterised by the ability to decouple the system vulnerability assessment from the climate uncertainty assessment. Central to the decision scaling approach is a system stress test that we use to identify climate parameters that have substantial impacts on the system performance. This alternative climate assessment approach provides an opportunity to qualitatively assess the value of using transient stochastic timeseries that are informed by climate projections and to provide context for climate projections sourced from other GCMs. Decision scaling may also serve to inform the climate modelling community of climate variables that are most relevant to assessing future climate risks to water resource systems.

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Acknowledgements:
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Keywords: *Climate change, water resource risk assessment, decision scaling, conceptual reservoir model*

EXTENDED ABSTRACT ONLY

Climate impact on environmental flow outcomes in the Goulburn system, Victoria: a decision scaling approach

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Abstract: Australian governments have invested billions of dollars in returning water to the environment, yet the risk to this investment posed by climate change and variability is not clearly understood. Traditional approaches to modelling climate change impacts on river systems have focussed on improving climate projections and incorporating these into water resource models using a small number of scenarios. A new suite of tools are now being developed that instead recognise the inherent uncertainty in future projections. These so-called bottom-up methods, including the "decision scaling" approach adopted here, all incorporate an element of "stress testing"—understanding how much perturbation a system can cope with before it fails. While these approaches have been applied to a number of water resource management situations, applications for ecological objectives have been limited. Here we present an innovative decision scaling methodology that assesses climate risks to delivery of environmental water, with application to connected rivers in northern Victoria (including the Goulburn, Broken, Campaspe and Loddon rivers).

Flow variability is key to moderating freshwater ecosystem conditions, and species respond to individual flow sequences through life-history traits. For example, if an ecosystem is already in poor condition due to a prior drought, it may not respond as hoped to an environmental flow release. This sensitivity is poorly explored in common approaches to assessing climate impacts based on historical sequences. In addition, climate impact assessments have so far ignored possible changes in rainfall runoff relationships affecting flow volume and sequences. Such changes were observed in northern Victoria during the recent Millennium Drought (~1997-2010). These have three implications for risk assessment: (i) stochastic data underlying 'bottom-up' approaches must contain realistic sequences of multi-year dry and wet periods typical of Australian variability; (ii) rainfall-runoff approaches are required that are able to represent possible future shifts in runoff generation; and (iii) ecological flow-response models must incorporate and be sensitive to past history of flow delivery.

To address the stochastic data challenges, we apply Complete Ensemble Empirical Mode Decomposition to isolate the low-frequency, ENSO-like behaviour in the rainfall data and stochastically generate this separately. A further challenge for stress testing is that the systems of interest are often too large to be treated as a single unit, yet many existing tools do not extend to multi-site analysis. Here we apply a multi-site Matalas stochastic generation scheme in a parsimonious manner to capture the spatial and temporal scales of most hydrological importance. Regarding rainfall-runoff modelling improvements, we describe advances towards models that are better able to track moisture deficits as they accumulate through long droughts. Ecological models that incorporate temporal sequencing already exist in the form of process-based models. These are better able to predict ecological outcomes under novel conditions, including extended dry periods. Mechanistic models may link a number of different locations or reaches in a river together (for example to represent fish movement) and allow for responses triggered by both inter and intra-annual flow regimes.

Even after the above innovations, many challenges remain. River operations have a large impact on ecology and need to be represented, but water resource models are detailed and cannot be run thousands of times to support the stress test. We propose a simplified system model fit for this purpose. Similarly, unless innovative solutions are applied, ecological modelling requires fine temporal scale resolution inputs, which increases computational requirements. Importantly, the factors most relevant to the ecological system – such as strength of ENSO-like behavior – may not be well informed by GCMs. This means that, while we can stress-test and discover the limits of system resilience, it may be difficult to relate this back to expected climatic changes over planning horizons. Many existing applications of stress-testing focus on permutations along two axes (e.g. average annual rainfall and temperature). Here we represent four axes (annual rainfall, temperature, seasonality and low-frequency variability), but vulnerabilities may also exist in others. Lastly, there is the challenge of communicating results from a multi-dimensional stress-test to decision makers and other stakeholders.

Keywords: *Decision scaling, integrated assessment, river systems modelling, mechanistic ecological models*

Challenges in combining hydrological and ecological methods to predict climate change risks to freshwater ecosystems

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Abstract: Freshwater ecosystems encompass some of the most productive and diverse environments yet are in decline globally due to human interference. Climate change further compounds existing threats through direct habitat impacts and environmental interactions, although our full understanding of ecological vulnerability is limited. Understanding climate risks to freshwater ecosystems requires combining hydrological and ecological knowledge, both of which face challenges in representing uncertainty through variability and non-stationarity. While there have been significant advances in both these disciplines and a large array of methods are available for undertaking impact assessments, the approaches are often not well-integrated, with key differences in spatial and temporal assumptions. Here we examine published literature to document the state of the art and better understand methodological choices for assessing of climate change impacts on freshwater ecosystems.

We explore the modelling options available for predicting hydroclimatic impact and ecological response, and discuss the benefits, shortcomings and future directions of each. Using a systematic literature search, we identify four groups of studies defined by the choice of hydrological and ecological methods. Each of the four groups represent a fundamental difference in the representation of and sensitivity to certain threats, the kinds of outputs expected from the analysis, and the handling of input uncertainty and variability. Choice and use of these four groups can lead to different assessments of risk when applied to the same case study. We highlight which combinations of methods are less useful under climate change, and advocate for commensurate approaches that can maximise the utility of complex and resource-intensive modelling while ensuring the effects of climate uncertainty and variability are captured.

The results suggest that research and modelling advances in hydrological and ecological disciplines have not been well integrated in climate change impact assessments. Unless the interactions between changing hydrologic variability and ecological response are explicitly considered, it is likely that the true risks of climate change impacts on freshwater ecosystems will be misrepresented, and this has implications for effective management responses. There is significant potential to improve our current understanding of risks to freshwater ecosystems by better capitalising on and linking the advances currently being made in isolation in the disciplines of hydrology and ecology.

Keywords: *Climate change impact assessment, ecological and hydrological modelling approaches, understanding and managing climate risk*

Modelling household water use: Using empirical data to inform continuous simulations

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Abstract: In recent decades traditional water management practices have come under stress from rising global populations and changing climate conditions. The prohibitive costs of upgrading centralised infrastructure networks to meet these changing conditions has encouraged research into the provision of integrated water management at the site scale, such as rainwater harvesting (RWH) or greywater re-use. Unfortunately, effective design, implementation and optimisation of these strategies has been restricted by uncertainties when quantifying how these systems will perform on each site. The reason for this difficulty is that there are many aspects of household or site scale hydrology that are poorly understood or difficult to model, including residential outdoor water use and garden watering. The accuracy and speed at which these aspects of site hydrology can be modelled is a vital consideration in the development of site scale water management.

This study aimed to improve the understanding surrounding the accuracy and usability of different strategies for modelling the interaction between the different household water uses. This will provide insight into how their effect upon site scale hydrology can be quantified in future studies and improve the design and optimisation of new integrated water management strategies. This was achieved by analysing four different strategies that each apply different assumptions to account for the three main end uses of household water use (indoor, garden watering and other outdoor water uses) that have been utilised or suggested by previous researchers for use within continuous/water balance simulations. These four strategies were each tested using historic water use data from 100 residential properties in Melbourne's eastern suburbs.

The 'lowest average water use' strategy assumed that no outdoor water use occurred during the month with the lowest average daily water use and that any variation from this value would be caused by outdoor water use. This strategy calculated a consistent indoor water use of 83.9 L per person per day with separate variable garden watering and other outdoor water use values that can be averaged across multiple years to find the average values per month. This method appeared to be promising as it was easy to use and returned results that were mostly logical. However the assumption that indoor water use is constant across the year should be questioned.

The 'wet or dry averages' and 'consecutive dry days' strategies both assumed that no outdoor water use would occur on days with rainfall and that any increase on days without rainfall would be caused by outdoor water use with possible reference to the number of consecutive days without rainfall. While these strategies were able to demonstrate that water use is lower on days with rainfall, and increases on days without rainfall, quantifying these findings produced illogical garden watering estimates. Daily indoor water use was calculated as 115.3 L per person with variable, and sometimes negative outdoor and garden watering values. It appears likely that either indoor water use did not remain consistent or outdoor water use did occur on days with rainfall.

The 'identifying peak usage' strategy was based upon the assumption that garden watering occurs a limited number of times each week and could therefore be identified by examining the higher water use values from each week. This strategy analysed garden watering only and did not attempt to separate indoor water use from non-garden based outdoor water uses. This strategy identified a gap between the higher daily water use values from properties with and without garden watering during some seasons. With the average property watering their garden twice a week using a combined total of 82.1 L per person during autumn and 59.3 L per person during spring. No garden watering was detected during summer or winter (the summer results may have been caused by an unusually wet summer or by missing data for some seasons from some properties).

Comparing the merits of these four strategies the 'lowest average water use' was the easiest to use, quickly providing logical results for both garden watering and other outdoor water use that were easy to visually interpret. Unfortunately the accuracy of this method relies upon the assumption of consistent indoor water use and this must be questioned. The 'identifying peak usage' strategy was more computationally difficult but returns a more realistic assessment of the water demand imposed by garden watering, including a weekly garden watering pattern. However this strategy could not separate indoor and other outdoor water uses. The selection of which strategy is preferable will therefore depend upon the needs of the individual study. By being aware of the different strengths and weaknesses that have been identified in this study, future designers will be better equipped to select the best strategy for their individual needs when working with site scale hydrology

Keywords: *Household water use, garden watering, seasonal variation, continuous simulation*

Stochastic model of urban water demand for water supply system planning

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Abstract: Traditional urban water supply planning is typically based on one or more scenarios of future demand. A typical set of scenarios may represent low, expected and high trajectories of future demand. However, historical observations of urban water demand show that it is intrinsically stochastic with low and high frequency variability. Indeed, historical trajectories often bear little resemblance to the stylized scenarios used in planning. To improve the robustness of water supply planning in the face of demand uncertainty and, in particular, optimization of the future schedule of options, it is argued that more realistic models of future urban water demand must be used in simulation models. The purpose of this study is to use historical observations of urban water demand to identify the important characteristics of a stochastic demand model that could be incorporated in the simulation of future system performance.

Uncertainty in future demand increases significantly as we move further into the future. Indeed the uncertainty may dominate the overall variability in future trajectories. For this reason, the focus is on identifying a simple parsimonious stochastic model with a minimal number of predictor variables. Annual total urban water demand (TUD) is modelled as a function of two stochastic variables, annual per capita consumption (PC) and annual population growth rate (PGR). For each variable, its expected value is given by a linear model of predictor variables and the perturbation about the expected value is an autoregressive moving average (ARMA) variate. The expected value represents the low frequency variability and is dependent on the predictor variables. We use historical observations of the predictor variables to identify the linear model and to guide development of stochastic models of predictor variables when generating future demand trajectories. The ARMA variate represents the higher frequency noise accounting for influences on demand not captured by the predictor variables.

Annual historical data from 1980 to 2016 for three Australian capital cities (Sydney, Melbourne and Brisbane) is used to identify the stochastic model. The data included time series of observed TUD, PC and PGR as well as time series of several predictor variables. The predictor variables included restriction level to capture regulated reductions in consumption during drought, climate variables [soil moisture index, maximum temperature, rainfall, and evaporation] to capture climate-dependent water use, and water efficiency indexes [group A (bathroom) and group B (kitchen and laundry)] to describe the transition in domestic water appliance efficiency as a result of the Water Efficiency Labelling and Standards (WELS) initiative.

Analysis of the data revealed a consistent pattern. For the PC variate, the linear model had a very high R^2 with the most parsimonious set of predictor variables being restriction level, maximum temperature and the two water efficiency indexes. The perturbations about the expected value of PC were small and were identified as white noise, that is, an ARMA(0,0) model. Because the transition to more efficient water efficient appliances has been largely completed by 2016, simulation of future PC will be depend on restriction level and maximum temperature and potentially other variables that describe the densification of urban areas from low-density detached dwelling to multi-unit dwellings. In contrast, no meaningful predictor variables were identified for the PGR variate. The PGR time series was dominated by perturbations about the mean value of PGR that were found to be described by MA models with lags of 3 to 4 years. Sustained runs above and below the mean PGR were observed and are attributed to difficult-to-quantify factors such as government immigration policies, internal migration from regional and interstate, economic and social performance of the city, and so on.

In view of the fact that PGR is dominated by ARMA variability, we expect that the trajectory of future demand will exhibit high variability. The incorporation of a stochastic model of PC and PGR into water supply simulation will ensure that optimization of future water supply schedules "sees" the intrinsically high variability in future demand and therefore forces the optimization algorithm towards identifying highly adaptive strategies.

Keywords: *Stochastic models, urban water demand, linear regression, autoregressive moving average, water supply system planning*

Modelling impacts of climate change on potential evapotranspiration in New South Wales, Australia

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Abstract: Potential evapotranspiration (ETp) is mainly influenced by climate factors including wind speed, air temperature, solar radiation, relative humidity. Thus, it is necessary to project the potential impacts of climate change on ETp. The physically-based Penman model is recommended as a standard model in ETp estimates. However, Penman model needs the complete set of the above-mentioned climate variables, which may limit its use in projecting ETp under future climate scenarios. Meanwhile, projection of future ETp may company with uncertainties due to the various ETp models, GCMs, and RCPs. It is important to quantify the relative contribution of these factors to the uncertainty in ETp projection.

In this study we developed three random forest-based (RF-based) ETp models with historical observed climate data at eight climatic stations in New South Wales (NSW). Performance of these RF models were compared with four empirical models (Jensen-Haise, Makkink, Abtew, and Hargreaves) requiring the same meteorlogical inputs with Penman model as the benchmark. Then, the RF-based and empirical models were used to project future ETp for the eight stations based on statistically downscaled daily climatic data from 34 GCMs under the RCP4.5 and RCP8.5 climate scenarios. In addition, we adopted the analysis of variance (ANOVA) method to quantify uncertainties in ETp projections originating from ETp models, GCMs, RCPs, and their combined effects.

Results showed that the RF-based ETp models generally outperformed the empirical models in estimating ETp across all stations, with higher R^2 and lower RMSE and rMBE values. ETp was likely to increase at the eight stations due to the increasing temperature and solar radiation. The ensemble increases of mean ETp across eight stations ranged from 33 mm year-1 (2.1%, 2040s) to 129 mm year-1 (9.2%, 2090s) and from 43 mm year-1 (2.8%, 2040s) to 248 mm year-1 (17.6%, 2090s) under RCP4.5 and under RCP8.5, respectively. As to uncertainty in ETp projection, results showed that RCP-related uncertainty contributed the most to projected ETp uncertainty (around 40% for most stations) while GCM-related and ETp model-related uncertainties accounted for roughly equal amounts of projected ETp uncertainty (10%-30%). This study highlights that RF-based ETp model are a promising method in projecting future ETp. Meanwhile, it is necessary to adopt multiple GCMs and RCPs to projection future ETp.

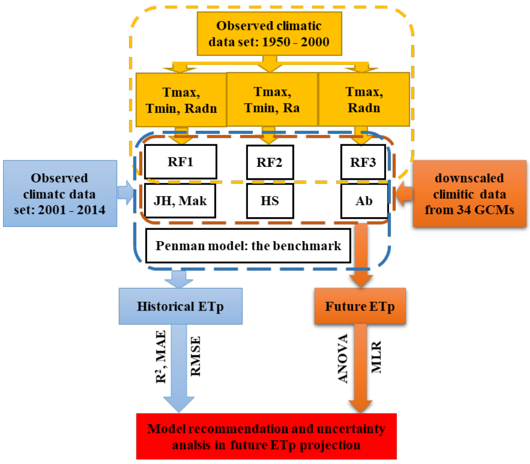

Figure 1. The flowchart of this study

Keywords: *Potential evapotranspiration, empirical ETp models, random forest, uncertainty, climate change*

An evaluation of statistical bias-correction and downscaling methods for hydrological impact studies

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Abstract: Hydrological impact studies investigate the effects of climate change on hydrological variables, such as changes in soil moisture, streamflow or hydrological extremes. The outputs of such studies are critical, for example, for ensuring sustainable and safe water resources management, food production or infrastructure development.

Hydrological impact assessments are commonly based on hydrological models forced with corrected outputs of general circulation models (GCMs) that simulate future climate conditions, including temperature, precipitation, wind or solar radiation, under a range of possible scenarios for future greenhouse gas concentrations. Due to very high computing requirements of climate simulations, the models are run at relatively coarse resolution– coarser than what would be required to force hydrological impact models. In addition, small-scale processes that are below the climate model resolution are approximated using parameterisations, leading to potential biases in some variables or processes. Therefore, bias-correction and downscaling methods are applied to outputs of climate models to remove any systemic biases and to increase the resolution of the model output to match the spatial resolution required by the impact models.

The Bureau of Meteorology (BoM) is currently developing a National Hydrological Projections Service that will provide estimates of future climate change impacts on Australian water resources based on an ensemble of: a) two scenarios for future greenhouse gas concentrations, b) four GCMs that have been assessed to be skilful for the Australian domain, and c) a range of statistical and dynamical bias-correction and downscaling methods. This presentation provides an overview of four statistical methods for producing bias-corrected and downscaled climate projections data employed at the BoM and the evaluation of these methods for hydrological impact assessments in Australia.

The following methods have been applied to raw GCM outputs: 1) a trend-preserving quantile matching approach developed for the Intersectoral Impacts Model Intercomparison Project (ISIMIP) (Hempel, Frieler, Warszawski, Schewe, & Piontek, 2013), 2) a statistical downscaling method (SDM) developed at the Bureau of Meteorology (Timbal, Fernandez & Li, 2009), 3) a multi-variate bias-correction and spatial disaggregation (rBCSD) method (REFs), and 4) a quantile matching empirical statistical downscaling method optimised for preserving extreme events (Dowdy, 2019). The Australian Water Availability Project data (AWAP; Jones, Wang, & Fawcett, 2009), a gridded dataset that contains climate observations (including precipitation, temperature) at 0.5 km grid resolution, was used as target dataset for the bias-correction and downscaling methods. Subsequently, we forced the AWRA-L (Australian Water Resources Assessment – Landscape) model, a gridded land surface water balance model, with the bias-corrected and downscaled outputs to produce hydrological simulations for the historical period (1950-2005). We evaluated the outputs against a historical reference run using AWAP data as climate inputs. We present the evaluation of bias-corrected and downscaled climate inputs (precipitation, temperature, solar radiation and wind) and simulated soil moisture, evapotranspiration and runoff over a 30-year period (1976-2005). The evaluation includes assessments of mean biases as well as biases in temporal variability and extremes – at seasonal, annual and multi-annual time scale. We discuss implications of our findings for impact assessments for water resource management and outline potential uses of these methods.

Keywords: *Hydrological projections, water resources modelling, flood, drought, risk assessments*

Development of an Atmosphere-Ocean-Geosphere-Coupled Model and its application to the Kanto plain, Japan

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Abstract: Water circulation between atmosphere and geosphere generates important feedbacks. Thus, a coupled model has been developed by combining the Multi-Scale Simulator for the Geoenvironment for Atmosphere (MSSG-A), for Ocean (MSSG-O) and the GEneral purpose Terrestrial fluid-FLOW Simulator (GETFLOWS) for surface-groundwater. The information exchange between the simulators is controlled dynamically by the OASIS coupler. The coupled model can handle short time (10min to daily), seasonal (several months to yearly) and potentially decadal (not implemented yet) water circulation. The model is used to investigate the influence of temperature, rainfall and evaporation on land surface run-off and ground water as well as soil moisture and latent heat on climate. An important application is to model the impact of future climate change and support sustainable development. The current paper focus on model description and mass-balance assessment. Some preliminary experiments were performed using a model with a 500m horizontal resolution, exchanging data every 10 minutes on 147 computing cores. The model covers the whole Kanto basin in Japan and is assessed over the period 21/07/2006 to 08/09/2006 that includes one extreme rainfall event. First, the water mass balance of the coupled model was estimated by comparing the aquifer water storage (groundwater, soil moisture and river storage) computed by the hydrological model and the water flux of the watershed such as rainfall, evaporation, river discharge and coastal exchange at the land-ocean interface. The coupled model achieved good mass conservation. In a second step, the present coupled model was validated with observation data. Comparison with rainfall station data showed that the model underestimated the rainfall at high elevation locations but overestimated the rainfall at low elevation locations. Despite these biases, the overall rainfall was well reproduced by the model. Comparison with gridded satellite derived TRMM rainfall data showed that the cumulative precipitation volume modelled in the domain agrees with the satellite observation with an error of 15% or less.

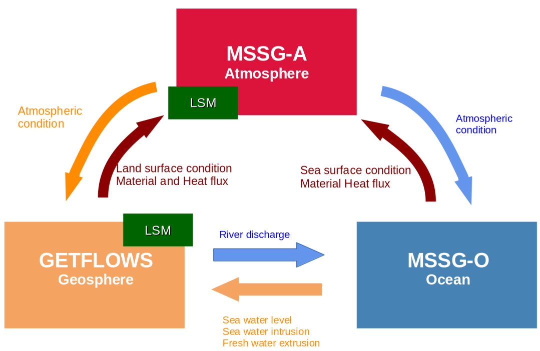

Figure 1. Schematic dynamic coupling strategy between ocean, atmosphere and geosphere model.

Keywords: *Atmosphere-ocean-geosphere model, dynamical coupling, Kanto plain*

Changing domestic water consumption during a heatwave: The importance of social factors

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Abstract: Australian cities face regular droughts. Since the last major drought on the Australian east coast, many Australian cities have invested in desalination capacity. This is expensive, has a high opportunity cost, and requires large amounts of energy to operate. Water conservation, on the other hand, is an essential, cheap, and effective tool in the water supply toolbox. Sydney's per capita domestic water consumption is considerably higher than that of Melbourne. Hence, there is considerable potential in Sydney to adopt water conservation programs as a key factor for managing water demand and supply. However, climate change projections suggest there will be more days over 40°C across NSW, and heatwaves are projected to occur more often and last longer. A heatwave is defined as "a period of unusual and uncomfortable hot weather for 3 or more days in a row" where maximum temperature exceeds 35°C. How households use water during heatwaves adds pressure on infrastructure as it increases peak demand which left unmanaged will require upgrades of pipe networks. This paper has two objectives: Firstly, to understand the relationship between residents, their stated water consumption patterns, and their stated intention to modify water-use behaviour during heatwaves; and secondly, to identify possible interventions that could help reduce the peak of water consumption during heatwaves and promote uptake of water conservation behaviour, such as targeting knowledge and satisficing behaviour. An online survey of Sydney households was conducted in November 2017, with 547 households recruited via an online research panel completing the survey. The survey included measures of respondents' current practices to save water inside and outside the home, their environmental beliefs, priorities, and motivations, their perceived social norms, beliefs about environmental vulnerability and behaviour control, and the likelihood of them engaging in a range of different behaviours during a heatwave.

Multiple regression analyses were conducted separately for homeowners and renters, to predict garden watering behaviours, water saving practices insider the home, water saving practices outside the home, and stated water consuming behaviours during a heatwave. For the latter, homeowners and renters produced similar results, with approximately 50% of the variance being predicted from general tendency to satisfice in making decisions, perceived social norms, engaging in social comparisons, and having confidence in knowing how to conserve water. Results for the other dependent variables showed the importance of environmental beliefs and priorities, social norms, perceived behavioural control, and confidence in knowing how to conserve water.

Findings from this research provides insights into potential water consumption behaviour during heatwaves, and the early warning signs that more water could be consumed during heatwaves, despite efforts to promote water conservation by the local water authority. Curbing excessive water consumption during heatwaves requires that householders know the importance of reducing water consumption, know what actions to take, feel able to take those actions, and are positioned to be able to take those actions. It is especially important that households know to reduce consumption at peak periods – not just daily use peak periods, but especially during heatwaves (doubly so during droughts).

***Keywords**:* *Domestic water consumption; heatwaves; social norms; behavioural control*

EXTENDED ABSTRACT ONLY

Decadal variability in historical record – short-term drought analysis for Warragamba system

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Abstract: High variability, especially high decadal variability (also known as long-term persistence) is a significant characteristic of climate in eastern Australia. That leads to the phenomenon that drought is a common and recurring part of the Australian climate. The vulnerability of water supply system to droughts depends on the interplay between streamflow variability and demands of the system. Thus, from the water supply perspective, a series of drought planning measures/actions are necessary when certain threshold triggers are met to prevent the storages from falling to an unacceptable level. Assessments, scheduling and optimizations of such drought measures/actions require a wide range of possible streamflow sequences, which are generated by different synthetic data generation algorithms.

Commonly used stochastic streamflow generating algorithms randomly sample from a parametric or a non-parametric distribution fitted to the whole historical record so that the generated streamflow sequences match a set of desired stochastic properties. These algorithms are developed with the aim of reproducing long-term historical observed streamflow characteristics and represent the "average" climate conditions. Thus, most of the algorithms do not take into account of the decadal variability in streamflow sequences, and are not able to generate a wide range of possible future climate conditions.

This paper divided the whole instrumental streamflow record of Sydney water supply system into 10-year periods and ranked these periods according to the total 10-year inflow of Warragamba inflow, and then form "artificial" instrumental streamflow records that have the driest, average and wettest three 10-year periods. This way, streamflow sequences generated based on the driest 30-year record represent possible future climate conditions that are different from streamflow sequences generated based on either the average or wettest 30-year record. This allows us stochastically assess water supply system during decades that the climate and hydrologic conditions are significantly different from the long-term average, and provides insights into a water supply system's response to different hydrological conditions.

Results show that all major reservoirs in the Greater Sydney water supply system exhibit strong differences in driest and wettest 30-year record. Ratios of mean and standard deviation to long-term mean and standard deviation mostly sit below 0.8 for the driest 30-year and above 1.2 for the wettest 30-year periods. 99% and 99.9% percentile depletion curve are also significantly different between wettest, driest and average 30-year periods. These conclusions are consistent between different initial total storage. In this way, the vulnerability of the water resource system and cost/benefit of certain drought measures/actions can be assessed for a wider range of possible future climate conditions.

Keywords: *Decadal variability, water supply system, synthetic data generation*

Fusing remote sensing data with numerical simulation to estimate historical water levels in Thirlmere Lakes

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Abstract: Similar to many wetland systems around the world, Thirlmere Lakes (TL), located in the Blue Mountains World Heritage area, has recently experienced declining water levels which has led to concerns about the causes of the changes and the future sustainability of the wetland. Monitoring the surface water in TL may provide useful information in understanding hydroclimate extremes. However, due to the limited resources, in-situ monitoring of water level data is often limited to relatively short periods and only a few locations. In contrast, satellite datasets provide a long period of records with a low cost for research purposes. Water extents are often derived from satellite imageries using, for example, NDWI (Normalised Difference Water Index); but the derived products do not have good temporal continuity and temporal resolution due to several interferences, including land cover types, cloud cover, and scene availability.

To deal with the problem, the present study adopts a concurrent remote sensing and numerical modelling approach to improve the estimation of historical water level in wetlands. Many studies have shown that areas of surface water on Earth can be extracted through satellite imagery by calculating the water index from the scenes obtained from Landsat Thematic Mapper (TM). However, the existing methods do not always have consistent results for water areas with standing vegetation as shown in Figure 1. Therefore, an improved water index method using Landsat TM is proposed in this study to better discriminate small water surface areas (~ 10^4 m^2) with standing vegetation from other types of cover in wetlands. The validation against ground measurements suggests that the extraction of water areas within wetlands was successfully achieved with significantly improved accuracy compared to the existing methods across different seasons (Figure 1). Subsequently, a numerical water balance model was adopted to estimate the continuous historical level for water bodies at TL. Using a data-driven modelling approach based on the remotely sensed water extents and the digital elevation model (DEM), fluxes between surface water and groundwater in the water balance model were calibrated as a group of lumped parameters. This was undertaken to improve the accuracy of water level predictions. The improved water level data compare well with the recent field measurements and depict a consistent trend with the remotely sensed data. Both temporal continuity and temporal resolution of the data were improved using the concurrent remote sensing and numerical modelling approach, with the temporal resolution refined by over 90%.

Further analysis of the continuous historical water levels highlights a close relationship between the level change in TL and historical drought periods. The results show that the surface water intermittency in TL was consistently observed at the beginning of each drought period in the past decades in NSW. The intermittent wetland data may provide a signal of the climatic variability. The change of dominant frequencies in the water level time series may also represent the altering hydroclimate in the local region. This study demonstrates the importance of adopting historical water level data obtained from the concurrent remote sensing and numerical modelling approach in hydroclimatic analysis.

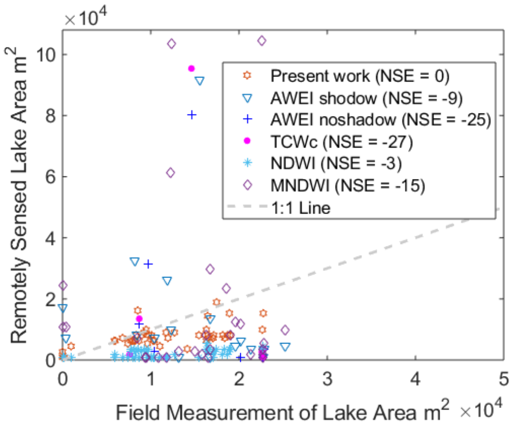

Figure 1. Comparison of the water areas derived from satellite imageries at different time instants against the field measurements with NSE (Nash–Sutcliffe Efficiency): 1) Present work, 2-3) Automatic Water Extraction Index (AWEI) with and without shallow; 4) Tasseled Cap Water Index (TCWc); 5) Normalised Difference Water Index (NDWI); and 6) Modified Normalised Difference Water Index (MNDWI).

Keywords: *Remote sensing, water index, water balance modelling, climatically intermittent wetlands*

A water-level based calibration approach of rainfall-runoff models

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Abstract: Traditionally, accurate rainfall-runoff prediction requires sufficient discharge time series as response data. However, since most catchments are ungauged and lack of discharge measurements, it is necessary to investigate a new calibration method that does not rely on discharge data entirely. This study uses water level data as a replacement to discharge data in modelling processes. And with the promising future of satellite altimetry data, this method could enable the calibrations in ungauged areas.

To implement water level data into rainfall-runoff modelling, a simple power-law relationship between discharge and water level is simulated by adding 3 extra parameters to a typical daily rainfall-runoff model (e.g. GR4J). The modelled discharge then can be transferred to modelled water level, and the model is calibrated against the ground-measured water level time series. In addition, two regionalised discharge signatures (the mean and 95th percentile of the discharge) are imported to constrain the modelling processes.

The results show that water level time series could provide similar fluctuations to the discharge data in hydrological calibration, and with the constraining effects of the discharge signatures, the new calibration approach could reproduce the discharge time series with high accuracy (median NSE of 0.63 in 130 Australian catchments). Among the catchments, wetter catchments tend to have better performance because they have better results in the discharge-based calibration and more accurate regionalised constraints.

Nevertheless, in real ungauged catchments, ground-measured water level data is not always achievable. One potential water level time series in these sites is the satellite altimetry. However, it is always associated with high uncertainty and low temporal resolution (e.g. 10-days). Towards extending the method to real ungauged cases, the robustness of the new method to the water level accuracy and resolution is tested. Since satellite altimetry data are only available at a few catchments, simulated altimetry data are used at this stage. The simulated altimetry data is generated by assuming a 10-days'cycle and adding different random errors (10%, 20% and 30%) to the ground-measured water level. The NSE values decreased slightly in most study sites, which means the water-level based calibration is robust to the observation error and low temporal resolution.

Overall, water-level based calibration provides a promising future to streamflow prediction in ungauged catchments. When simulated satellite altimetry data are used, the method is still reliable. Future work will focus on utilising the real altimetry data and testing the performances in real ungauged areas.

Keywords: *Rainfall-runoff modelling, water level, ungauged catchment, discharge signatures, simulated altimetry data*

Combining geophysical variables for maximizing temporal correlation without reference data

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Abstract: Geophysical datasets are important for understanding the principles of nature. Ground-based measurement is a classic way to obtain geophysical information, but is generally limited in space and time. Satellite and model-derived geophysical estimates can be an appealing alternative to ground measurement due to improved spatiotemporal availability. However, these estimates generally have their own advantages and weaknesses, and there is still room for improvements in their performance. To achieve this, many efforts have been made through de-noising, filtering and merging.

Here we focus on merging existing satellite- and model-derived datasets for improved measurement of geophysical variables. Such satellite- and model-derived variables have shown complementarity in their performance in terms of statistical metrics such as bias, root mean square error, and correlation coefficients. This complementary behaviour results from their different skills under different physical/ climatological retrieval conditions. For remote sensing data, the ability to capture temporal variability has been regarded as important in many applications. A linear combination of data sets is a simple but effective way to take the strengths of the original products to achieve better performance. However, a limitation is that calculating optimal weight assigned to each original product during the linear combination needs a truth reference that is often not available and thus hinders their practical applications. The extended triple collocation (ETC) approach does not have this limitation and it can provide error variances and Pearson correlations of the parent products against (hidden) truth without any reference data. The ETC approach has been widely used for uncertainty estimation of environmental variables (e.g. soil moisture, rainfall), but it has not been directly used for data merging, especially for maximizing correlation.

The aim of this study is, therefore, to develop a merging approach which can take advantages of both a linear combination and ETC approach. That is, we derive a linear combination method maximising correlation using data-truth correlations derived from ETC. For this, we first present the theoretical background of the proposed method and then verify it through synthetic experiments. In addition to this, we also perform the ETC-based combination scheme using various satellite- and model-derived soil moisture data. Finally, the combination results are compared to ground-based measurements.

Keywords: *Extended triple collocation, soil moisture, combination, merging, correlation*

Using an artificial neural network to enhance the spatial resolution of satellite soil moisture products based on soil thermal inertia

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Abstract: High resolution soil moisture information is vital for a number of environmental applications including hydrologic and climatic modelling. However, the available point-scale field measurements and coarse spatial resolution satellite soil moisture products (~10s of km) are unable to provide the spatial resolution requirements for many of these applications, especially at regional scales. Downscaling the L-band satellite soil moisture products appears to be a viable solution for this problem. Many research teams have tested methods and algorithms to downscale the satellite soil moisture retrievals, yet there is no universally applicable model. Among those methods, thermal data based downscaling models have shown promising results over arid and semi-arid regions.

The downscaling approach, based on the soil thermal inertia relationship between the diurnal temperature difference (ΔT) and the daily mean soil moisture (μ_{SM}), is one of the thermal data-based downscaling methods tested in the United States and Australia. These studies have used this method by building regressions between ΔT and μ_{SM} modulated by the vegetation density. However, there are a number of possible factors affecting the linearity of this regression model. Therefore, this study employed a machine learning model to build a more complex algorithm between ΔT, μ_{SM} and vegetation density. The Global Land Data Assimilation System (GLDAS) derived 25 km resolution ΔT values (from 2000 to 2017) and aggregated Moderate Resolution Imaging Spectroradiometer (MODIS) derived Normalized Difference Vegetation Index (NDVI) values were used as inputs, whereas GLDAS derived μ_{SM} values were used as targets to train an artificial neural network (ANN). The Levenberg-Marquardt algorithm with 50 hidden neurons was used as the network architecture in building this model. Thereafter, 1 km resolution MODIS derived ΔT and NDVI values of November 2005 were input into the model to estimate soil moisture at high spatial resolution (1 km). The estimated soil moisture values were then used to downscale aggregated NAFE'05 airborne soil moisture retrievals. The downscaled soil moisture products were compared with the 1 km resolution soil moisture retrievals from the National Airborne Field Experiment 2005 (NAFE'05). This study has been conducted over two medium-scale catchments, Krui and Merriwa River, located in the Upper Hunter region of the south-eastern Australia.

The comparison between downscaled and airborne soil moisture showed root mean square errors (RMSE) of 0.088, 0.072 and 0.058 cm^3/cm^3 on 7th, 14th and 21st November 2005, respectively. The downscaled soil moisture products were able to capture the detailed spatial patterns of soil moisture over the study area, showing a good match with the airborne retrievals. However, the algorithm performed better under dry catchment conditions compared to wet catchment conditions.

Keywords: *Artificial neural network, downscaling, soil moisture, Levenberg-Marquardt algorithm, machine learning*

Soil moisture retrieval depth at P- and L-band: simulations and observations

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Abstract: Soil moisture provides important information for economic, social and environmental planning in water-limited areas. However, global-scale soil moisture products derived from microwave remote sensing are limited to a relatively shallow depth, which is commonly held to be within the top 5 cm at L-band (~21 cm and 1.4 GHz). This research hypothesizes that P-band (~40 cm and 750 MHz) has a significantly larger moisture sensing depth than available L-band data due to its longer wavelength; a significant reason for pursuing this technology in the next-generation soil moisture satellite missions. To achieve this goal, both theoretical and empirical analysis has been carried out based on simulations and observations, respectively. Extensive radiometer TB (brightness temperature) observations at P- and L-band, together with corresponding soil moisture time series observations, have been collected at a tower-based experiment site which was established in October 2017 in Cora Lynn, Melbourne, Australia.

While there is a consensus that the longer the wavelength the greater the moisture sensing depth should be for a given moisture condition, it has not yet been proven because the definition of moisture sensing depth is somewhat vague and is thus not straightforward to be quantified. In this research, moisture retrieval depth is proposed and defined as the depth below the surface over which the averaged soil moisture produces a Fresnel emissivity that equals to the integrated thermal weighting function from the coherent model. The rationale is that the TB calculated by the coherent model could be regarded as a theoretical reference for retrieving near-surface soil moisture with the commonly used radiative transfer approximation. Based on this definition, the moisture retrieval depth can be theoretically estimated for a given moisture profile.

The theoretical results show that, overall, P-band has around two to three times larger moisture retrieval depth than L-band. The moisture retrieval depths at P- and L-band can respectively reach around 5 cm and 1 cm for an intermediate moisture condition (from 0.02 cm^3/cm^3 at the top to 0.2 cm^3/cm^3 at 50 cm in depth), and around 25 cm and 10 cm for a dry profile (0.02-0.1 cm^3/cm^3). Under extreme wet conditions (0.35-0.4 cm^3/cm^3), the moisture retrieval depth cannot exceed 1 cm even at P-band. Moreover, it was found that the moisture retrieval depth drops very quickly as frequency increases from 0.3 GHz to 2 GHz, getting close to zero at 2 GHz onwards. The empirical results show a decreasing correlation between the soil emissivity and the averaged soil moisture over an increasing soil thickness, indicating that neither P- or L-band achieves a 10 cm moisture retrieval depth under intermediate moisture conditions. However, the emissivity at P-band is observed to be better correlated to soil moisture than that at L-band. For example, the H-polarized channel at P-band had a better correlation (-0.83) over 10 cm than that (-0.79) over 5 cm at L-band, suggesting that P-band has the potential to obtain soil moisture over 10 cm in a practical sense if not in a theoretical sense.

Keywords: *Soil moisture retrieval depth, penetration depth, P/UHF-band, microwave remote sensing, coherent model*

Australian coastal catchment river discharge dataset for marine reanalysis modelling and forecasting application

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Abstract: Availability of gap-filled discharge datasets in coastal catchments in Australia is currently scarce and where these global datasets exist, they are currently at monthly scales for the largest global gauged catchments, or in smaller wet areas of Scotland and Northern Ireland. A key component to the success of any hydrodynamic shelf water modelling approach is the availability of robust estimates of river discharges along the relevant coastal boundaries. A first of its kind dataset covering both gauged and ungauged coastal catchments of Australia was created for the marine modelling community in coordination with the University of Tasmania (UTas) and the Commonwealth Scientific and Industrial Research Organisation (CSIRO), as part of the development and expansion of the Marine Virtual Laboratory (MARVL). The Coastal project provided a historical gap filled continuous discharge data using lumped and semi-distributed modelling at 405 gauged catchment *End of System (EoS)* locations and 771 ungauged catchment *EoS* locations and 60 CSIRO coastal node locations for the Great Barrier Reef region, for the period 1993 and 2016. The catchments considered in this project cover a combined area of 3,549,000 km^2 (Figure 1).

EoS locations for gauged catchments are chosen at the most downstream gauges based on: (i) data availability; (ii) no tidal effect; and (iii) model availability for gap-filling. Gauged data for *EoS* locations underwent considerable manual and automatic quality assurance and quality checked procedures, following which flagged values were eliminated and a gap-filling algorithm was used to create a final continuous discharge dataset at each of the 405 chosen gauging locations. Artificial coastal nodes for ungauged catchments are prioritised in each Drainage Division based on Australian Hydrological Geospatial Fabric (GeoFabric) analysis, comprising of externally draining catchment sizes of over 100 km^2. As this project is a first step, therefore the high temporal resolution (hourly) streamflow data generated in the Great Barrier Reef (GBR), whilst the daily streamflow data generated for rest of the Australia. The Grid to Grid (G2G) model was developed by the Centre for Ecology & Hydrology (CEH) in the United Kingdom (UK), is used to generate hourly streamflow simulations from gauged and ungauged catchments of GBR region and aggregated to 60 CSIRO coastal nodes. Ungauged streamflow outside of the GBR was generated using parameter estimates of the GR4J model runoff from the upstream or nearby gauging catchments within the same Köppen climate zones. The inverse distance weighting of all generated streamflows was then used as an estimate for daily discharge at the ungauged node.

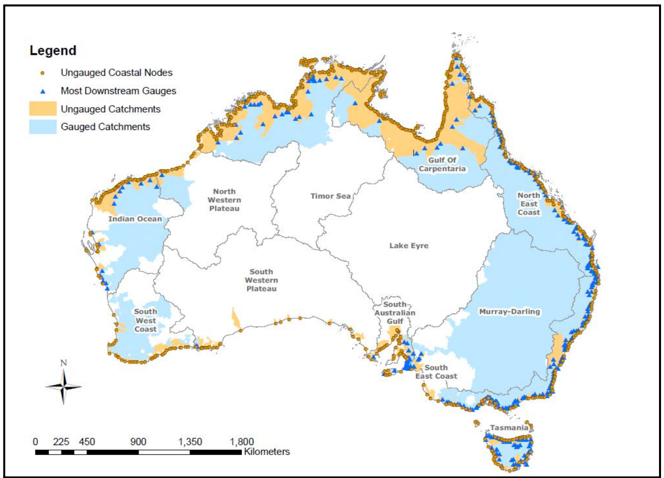

Figure 1. Location of gauged and ungauged catchments discharging to the entire Australian coastline

Improved availability of historical climate data and improvements to hydrological measurements provided the basis for estimating ungauged catchment discharge for rivers discharging into the ocean. The completed dataset will provide ameliorated avenues for improving constituent discharge estimation into the marine environment and serve as the boundary conditions for ocean shelf modelling. The streamflow dataset generated here covered the majority of the gauged and ungauged catchments in Australia, particularly in the regions where majority of Australian population is based. Therefore, this dataset could also be useful to assess the streamflow volumes in densely populated areas. This dataset is available for download in NetCDF format through this link, and is also available on the NCI data catalogue.

Keywords: *Coastal catchments, marine virtual laboratory, ungauged estimation, discharge dataset*

Incorporating palaeoclimate reconstructions into stochastic water resource analyses

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Abstract: Water resource analyses are highly sensitive to the hydrologic variability at a site, and to understand this variability, hydrologists need sufficiently long records. For storage yield analyses, Pretto et al. (1997, Water Resources Research) show that sequence lengths of 1000 years or more are required to identify a steady state estimate of storage capacity. For stochastic generation of hydrologic data, Thyer et al. (2006, Journal of Hydrology) demonstrate that depending on the persistence structure of annual rainfall, record lengths of at least a hundred and possibly more than 500 years are needed to identify a stochastic model and estimate its parameters. However, instrumental records are rarely this long. In Australia, the longest annual instrumental records of rainfall and streamflow are approximately 160 years long, with most records being much shorter.

Palaeoclimate reconstructions can be much longer than instrumental records. Published seasonally and annually resolved reconstructions of hydrologic variables in Australia have a median length of approximately 350 years, and a maximum length of over 1000 years. Therefore, palaeoclimate reconstructions provide a potential opportunity to better understand long-term hydrologic variability at a site. However, there are aspects of published palaeoclimate reconstructions that impact their use in water resource analyses. These include the amount, type and treatment of uncertainty, the reporting of relevant model parameter metrics and the relevance of the reconstructed variable.

Given the potential value of palaeoclimate reconstructions to water resource analyses, but also their limitations, here we investigate the properties of reconstructions that are important to be preserved in stochastic water resource analyses, using techniques such as Complete Ensemble Empirical Mode Decomposition (Figure 1). Further, we investigate how to inform a stochastic model with properties of both instrumental records and palaeoclimate reconstructions.

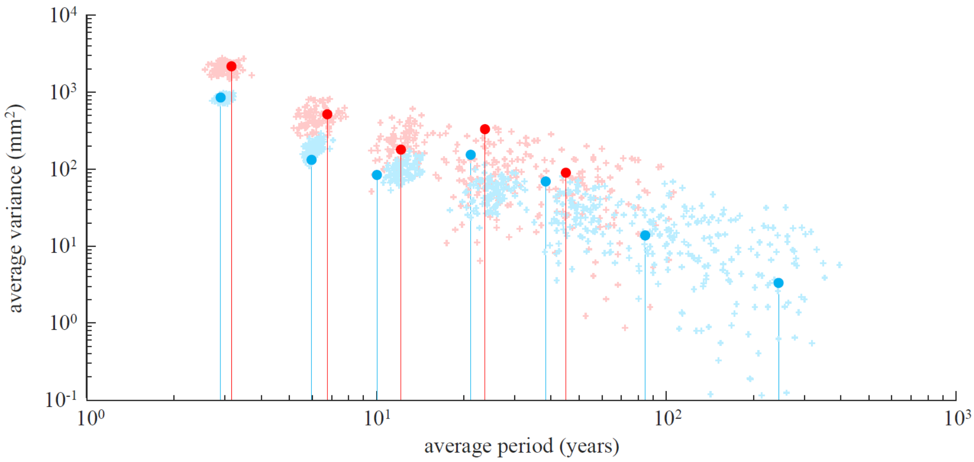

Figure 1. Exploration of the spectral properties of a palaeoclimate reconstruction of rainfall and its corresponding instrumental record, using Complete Ensemble Empirical Mode Decomposition. Circles represent Intrinsic Mode Functions (IMFs) of the instrumental (red) and reconstructed (blue) records. Crosses represent IMFs of replicates of uniformly distributed white noise with variance and length equal to the instrumental (red) and reconstructed (blue) records.

Keywords: *Water resources, palaeoclimate reconstructions, instrumental records, stochastic modelling*

Unknown knowns: when you don't understand your model as well as you think you do

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Abstract: Methods for predicting model errors and understanding model uncertainty must, by necessity, make some assumptions about how models behave. However, even simple models can behave in ways that are unexpected by the modeller. This may be because the model is chaotic, making its behavior inherently unpredictable. More commonly, the problem is with the modeller's expectations: he or she may not have sufficiently considered how model behavior can change under different circumstances. We present three examples from our work on hydrometeorological forecasting systems, where we attempted to predict model error and uncertainty but were confounded by unexpected model behavior.

The first example is our attempt to predict errors in hydrological models run at the hourly time step. We had previously developed an error model for hydrological models run at the monthly time step. This error model assumed errors would follow a Gaussian distribution (after transformation), an assumption that was supported in practice: it functioned very well in a range of conditions. However, our goal was to use the error model at an hourly time step. When we applied our error model at the hourly time step, it functioned poorly: errors were not Gaussian. We were unprepared for how the much higher autocorrelation of streamflow at shorter time steps impacted model errors. This caused a distribution that was far too sharply peaked to be represented by a Gaussian distribution. We addressed this problem by using a Gaussian mixture distribution, as well as applying different distributions to rising and falling limbs of the predicted hydrograph.

The second example is our application of statistical calibration to different weather prediction products derived from Numerical Weather Prediction (NWP) models. Statistical calibration of NWP models is often necessary to correct biases, reduce forecast errors and quantify forecast uncertainty, allowing the forecasts to be used in downstream (e.g. hydrological) models. We developed a method to calibrate deterministic NWP forecasts that functioned well. NWP models are chaotic, and a well-established principle in NWP forecasts is that ensemble predictions tend to be more accurate, on average, than deterministic predictions. Accordingly, we attempted to calibrate an ensemble NWP product, which averaged several deterministic NWP models. In this case our calibrated forecasts had a serious flaw: when rainfalls were accumulated over the forecast, our uncertainty bounds were too wide. This problem was also related to autocorrelation: averaging a range of NWP models tends to smooth out rainstorms in space and time. We discuss prospects for correcting this problem in future.

Our final example is of developing an error model for hydrological models of highly ephemeral catchments. We had developed a new method that should, in theory, have reliably quantified the uncertainty in catchments that stopped flowing >50% of the time. Initially our new method did not outperform an existing and much simpler method. This is because we assumed that the hydrological model would produce zero flows. In practice, it did not do so, and our error model failed. Only when we accounted for the hydrological model's inability to produce zeros did our error model function as we expected.

We conclude that missteps such as those presented here often lead to a deeper understanding of specific models, and of model behavior more generally.

Keywords: *Predictive uncertainty, model error, scientific method*

Hydrological Betamax: a parable of good modelling that failed badly

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Abstract: As modellers we like to focus our attention on developing the best possible model. Developing a bespoke solution that beautifully matches model complexity with data availability, with outputs that are targeted to address the problem objectives of most importance, requires considerable effort and focus. It can both be very challenging and satisfying. However, should creating the best possible model always be our prime focus? Are there situations in which spending less effort to develop a sub-optimal model might actually provide better outcomes?

This is a story about a modelling failure relevant to the estimation of logging on streamflow yields and water quality. It's a hydrological parable for the fate of the Betamax video recorder: everyone agreed it had the best technology, but it was a commercial flop that was bested by JVC's inferior VHS format. Our brief was to provide an independent estimate of the potential impacts of logging based on best available science, where it was hoped that such information would aid the development of an agreement between government and community stakeholders. We had more budget than time, and the technical challenges faced by the team in the time available were immense. We formed a crack commando unit of the best modelling brains from across three different agencies. We had the "A team". We developed bespoke modelling tools that were based on the latest science. The level of modelling complexity was commensurate with the available data, and the model outputs were carefully crafted to suit the questions being posed. We wrote a well-considered report that thoughtfully presented the outcomes in a manner that could be supported by the available evidence. In a technical sense we did everything right, and we delivered high-quality advice within the required timeframe.

However, we missed focusing on an essential ingredient: the true needs of the stakeholders. While our contractual client stated that their paramount concern was for the scientific defensibility of the outcomes, the real problem was that none of the stakeholders trusted the process put in place by the government. Our prime challenge was thus not the technical content of our advice, but rather the way we went about developing it. In the face of increasing tensions and the evident erosion of trust, our response was to work even harder on developing the best possible technical product. We completely failed to build a trusted relationship with the stakeholders and we never looked up from our keyboards long enough to notice. Consequently, the project was an abysmal failure. The project outputs were binned, and our efforts were indeed totally wasted.

This is a story about the fallibility of relying on good science and sound modelling to solve a real-world problem. We may well prefer to focus on the technical aspects of a problem, but this story illustrates how we might have more impact if we invested less effort in the science, and gave more attention to our communication and engagement skills.

Keywords: *Integrated modelling, integrated assessment frameworks, conceptual model*

How failure in bioenergy systems modelling led to an ensemble forecast based dam release model

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Abstract: In environmental and water resources systems analysis, optimisation is commonly applied to solve complex decision models for planning and management purposes. This presentation will tell a story of how failure to solve a mixed integer facility location model to optimise the siting of bioenergy refineries using conventional techniques has led to ideas that today, 5 years later, underpin an innovative dam release model. Conventional branch-and-bound and branch-and-cut methods to solve the bioenergy model failed because of the presence of a large number of binary decision variables. As is well reported in the literature, when using these conventional methods to solve large integer or mixed integer problems, the model solution time is often prohibitive. Failure to solve the bioenergy model led to the development of tabu search and kernel search heuristics that relied on the ranking of the binary variables to select a subset to exclude so to reduce the problem size and with that, the model solution time. Today, that same idea to rank binary decision variables to exclude certain ones forms the basis for an ensemble forecast based dam release model capable of explicitly considering each individual forecast trace, and by that, capable of explicitly limiting the risk of overflow at downstream locations. This is not easily achievable with the large majority of existing approaches in the literature, and hence, is a key advancement towards ensemble forecast based decision-making in reservoir operation. The story of how failure leads to exploration then innovation is typical in research but seldom recognised. It is hoped that researchers of all levels will find this presentation of interest.

Keywords: *Optimisation, systems analysis, mixed integer programming, facility location problem, reservoir operation*

The value of local knowledge: a bump in the road to using the ecohydrologic model RHESSys

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Abstract: We identified the ecohydrologic model RHESSys as a useful tool for addressing nonstationarity in catchment response under climate change. RHESSys is spatially distributed and resolves a range of processes such as nutrient cycling and vegetation growth at the patch, hillslope and watershed scales. It has been used by research groups in the USA to assess ecological responses to climate shifts, along with resulting impacts on hydrologic response (Tague et al., 2009, Bart et al., 2016).

Our intention was to use RHESSys as a virtual laboratory to run catchment experiments via simulations that could realistically represent sensitivity of catchment response to changing conditions. The first step was to see whether RHESSys could capture observed nonstationarity in catchment response. A number of hydrologically nonstationary catchments have been identified by Ajami et al. (2017) and we built models of several of them. However, we were unable to replicate the observed changes in runoff ratio. RHESSys vegetation parameters are defined based on North American forests, so we thought we might have more luck simulating a catchment in the USA. We applied the method of Ajami et al. (2017) to identify a suitably-sized catchment in the USA with a statistically significant shift in runoff ratio. After excluding catchments where the data seemed suspect, we were left with Flat Creek in North Carolina. The vegetation looked unusual on satellite imagery, but given there was no second option, we went ahead with it.

The first issue we noticed was that the model was not able to replicate the observed nonstationarity in runoff ratio. There were no statistically significant shifts in the climate data, so perhaps it was unlikely that climate was directly changing catchment response, and adding an estimated series of increasing carbon dioxide concentrations didn't improve the results. This left us confused as to where the observed nonstationarity was coming from – a check of Landsat imagery over time didn't reveal any obvious explanation such as land use change. We also noticed that the water table was around 14m deep in the model, meaning that it was far removed from the plant roots – of course, this explains why the ecological effects of increased carbon dioxide had minimal hydrologic impact. The model was subject to high equifinality. Since the dataset only contained streamflow data at the one gauge and we didn't have in-situ measurements of soil moisture or other variables to constrain model behavior, it was difficult to trust that catchment response was being represented properly.

We connected with one of the developers of RHESSys and discussed our problem. He had also worked near our study catchment and was able to tell us that it was part of an army base that had started a re-greening program in the mid-2000s. It wasn't enough to show up clearly on the Landsat imagery, but enough to cause the observed runoff ratio shift. This made the catchment completely inappropriate for our assessment, since we wanted to simulate climate-driven nonstationarity in catchment response. In addition, the sandy soils in the area meant that the 14m water table depth we had initially simulated was actually fairly realistic for that area. Hence, the model would not be appropriate for studying vegetation-water interactions.

While the fact that we couldn't use the model was disappointing, going through the process improved our knowledge of the software and helped us identify several new research questions. We are now working towards addressing these questions in collaboration with researchers who were able to provide a working model of a more suitable catchment. Our experience demonstrates the value of local knowledge in modelling studies. Important local information is sometimes difficult to find and it is advantageous to reach out to others with experience working in the area.

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Keywords: *Model fail, ecohydrology, land use change, catchment nonstationarity*

INVITED PAPER

EXTENDED ABSTRACT ONLY

Toward real-time operational flood forecasting using a probabilistic event-based framework

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Abstract: Floods are one of the most hazardous and expensive natural disasters. Flood warnings provide information about the timing and magnitude of the impending floods, which can help mitigate the risk of flooding. However, achieving accurate and reliable forecasts is hindered by inherent uncertainty that arises from different sources. This uncertainty is amplified and propagated through hydrological models. The natural variability in input forecast data (i.e., rainfall depth and spatio-temporal patterns) and antecedent wetness of the catchment are recognized as two important sources of uncertainty. Such sources of uncertainty should be identified and adequately quantified so that the decision-makers can reliably evaluate risk management options.

Ensemble-based techniques have been widely used to help characterize uncertainty in operational flood forecasting. However, little attention has been given to the application of these techniques to event-based hydrological models. Event-based models are simple and parsimonious and are thus widely used by practitioners for flood forecasting. Practitioners commonly undertake flood forecasts in a deterministic fashion, using single estimates of rainfall and manual adjustment of model parameters to account for current catchment conditions. However, such approaches are unable to emulate the inherent uncertainty in rainfall forecasts and in observation errors in current rainfalls and streamflows. Sequential updating schemes can automatically reproduce observation errors, model uncertainty, and its propagation, and they can help improve the forecast skill in time. Therefore, there is a scope to investigate the efficacy of using an ensemble-based approach coupled with an updating scheme with event-based models for operational flood forecasting.

We develop an ensemble-based framework which uses an event-based storage-routing hydrological model to produce flood forecasts. We find that the framework can readily accommodate uncertainty in model loss parameters, initial loss (IL) and conditioning loss (CL), as well as the uncertainty in the rainfall forecasts. A sequential re-calibration scheme is adopted to reproduce observation errors up until the time of the forecast, and these sources of uncertainty are included in the forecast ensemble.

In this study, the ensemble of catchment losses is derived using the Australian Water Resource Assessment – Landscape (AWRA-L) soil moisture data, and ensembles of rainfall forecasts are synthetically generated to emulate the performance of available Poor Man's Ensemble forecasts provided operationally by the Bureau of Meteorology. The errors in the observed streamflow are based on rating curve analyses and are used to generate an ensemble of perturbed observed streamflows. Similarly, the errors in observed rainfall are estimated by comparing point gauge observations with areal estimates obtained from using Australian Water Availability Project (AWAP) rainfalls, and these are used to generate an ensemble of observed input rainfalls. A Monte Carlo simulation approach is then used to stochastically re-calibrate model loss parameters in a manner that accounts for errors in the observed input data. As illustrated in Figure 1, the skill of the forecast scheme is heavily dependent on whether the re-calibration-based IL/CL update is applied prior to or after the streamflow rise has commenced. However, once the catchment responds to rainfall, the uncertainty of ensemble forecast is progressively reduced as more information becomes available during the course of the event. Analysing ensemble flood forecasts for 30 independent events shows that while there is little skill in forecasts which are based solely on prior estimates of catchment wetness, the reliability and accuracy of the forecasts improves rapidly as the flood event progresses. This study shows that as long as the adopted assimilation scheme gives appropriate consideration to the errors in observed and forecast data, ensemble forecasts can be implemented with the type of event-based models that are favoured by practitioners.

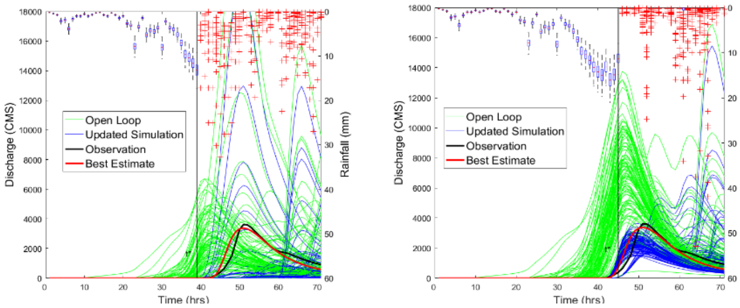

Figure 1. Ensemble of updated hydrographs of flood forecasts (blue lines) at t*

Keywords: *Ensemble-based forecasting, data assimilation, event-based models.*

Improved flood forecasting using convective-scale hydrometeorological ensembles: a forecast sensitivity study

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Abstract: Flooding is New Zealand's most frequent natural disaster with an average annual cost of approximately NZ$51 million. Accurately forecasting convective and orographically enhanced precipitation for hydrometeorological ensemble prediction systems is challenging in New Zealand's complex topographic, steep and fast responsive catchments. Globally, the design of initial condition perturbations for convection-permitting ensembles is still a work in progress. Given operational, computational and model representation constraints, a compromise is often required between key configurations: ensemble size, frequency of forecast issue times and model initialisation, weather model physics and resolution, domain size and data assimilation (DA) strategies. Although post-processing raw precipitation forecasts for hydrometeorological applications is essential to remove biases and produce reliable ensembles, a consistent long-term forecast archive is required, and an accurate representation of rare events can be difficult to model. The use of dynamical ensembles can improve predictive skill based on physical process representation and model initialisations. Central to this research is the presumption that by better understanding uncertainties and sensitivities of hydrometeorological forecasts during flood events (and quiet times) through varying weather ensemble configurations, we can be better placed to provide enhanced ensemble designs for future operational flood forecasting systems.

To understand and quantify the impact of various factors in flood forecasting uncertainty, we have considered hindcast simulations for several recent flood events (e.g. 5, 20, 500 year) in multiple case study catchments in New Zealand. The experiment design allowed for the impact of global versus local DA in the weather model, domain size and model resolution at 1.5km, 4.4km and 12km (and thus the representation of orography) to be investigated using weather model ensembles from consecutive initialization times (a "lagged ensemble"). Furthermore, the model physics, via the use of explicit and parameterised convection, the geographical bias across model configurations and resolutions, and the comparison of dynamical and statistical ensembles from the same initialisation time were also considered for their impact on flood forecast skill.

The weather model used is a local implementation of the UK Met Office-developed Unified Model. The New Zealand Convective-Scale Model (NZCSM) is NIWA's 1.5km high resolution operational forecast model, configured such that convective processes are allowed to develop explicitly. The New Zealand Ensemble (NZENS) is configured with similar model physics but operates with a 4.5km resolution and features up to 18 forecast members. The New Zealand Limited Area Model (NZLAM) is run on a much larger model domain, covering New Zealand, the Tasman Sea and the eastern seaboard of Australia. Three variants of NZLAM were run. NZLAM12 is NIWA's current operationally run configuration, using parameterised convection, while NZLAM4 is a 4.4km resolution version of the model run with two different science packages (GA uses parameterised convection and RA allows explicit convection).

Flood forecasts were produced by coupling the various weather ensemble configurations with the hydrological model TopNet and its built-in statistical ensemble generation tool. The distributed hydrological model TopNet is based on TOPMODEL concepts of runoff generation controlled by sub-surface water storage. Model parameters are based on nationally available information on catchment topography, physical and hydrological properties derived from a River Environment Classification, soil, land use and geology databases. Model parameters are therefore independent of biases in input rainfall forecasts and are estimated using the same method in both gauged and ungauged catchments.

Preliminary results show flood forecasts are most sensitive to convective-scale forecasts with consecutive issue time initialisations (lagged ensemble) over other hydrometeorological ensemble configurations considered.

Keywords: *Floods, ensemble forecasts, convective-scale, initialisation, operational configuration*

Towards seamless National Water Services for forecasting and climate risk strategy

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Abstract: The Bureau of Meteorology is close to releasing a seamless national landscape water service, bringing together historical water data from 1911 with short-term and seasonal forecasts and climate impact projections, using a single hydrological model, in a modelling system comparable across time. Seamless weather and climate risk modelling has been identified as a grand challenge of priority for the meteorological community. In the meteorological and climatological community, numerical weather prediction models (NWPs), general and regional circulation models (GCMs and RCMs) are run using different resolutions, inputs and physics for historical reanalysis, short, medium and seasonal forecasting and decadal projections – and are therefore subject to different biases. This makes bringing together forecasts and projections with historical information difficult for users. However, the nature of hydrological modelling - where (i) the same model is often used for all time-scales historical through to projections, (ii) model calibration is performed using reference forcing data sets and (iii) the forcing data from NWPs, GCMs or RCMs is post-processed (corrected) to match the same reference forcing data, results in a temporally comparable system across historical, prediction and future projection time-scales. The Australian Landscape Water Balance (ALWB, www.bom.gov.au/water/landscape), currently delivers national, operational estimates of rainfall, runoff, soil moisture in 3 layers, potential and actual evapotranspiration and deep drainage, on a 5 km grid, daily and up until yesterday. Behind this service is the Australian Water Resource Assessment Landscape model, AWRA-L, co-developed by the Bureau of Meteorology and CSIRO. Figure 1 outlines how the AWRA-L model will be used to provide a quasi-seamless water climate service.

The Landscape Forecasting project will extend the ALWB to provide ensemble short-term (out to 9 days) and seasonal (monthly to 6 months) forecasts of runoff, soil-moisture and evapotranspiration, nationally, at the 5 km resolution. Short-term dynamic hydrological forecasting is performed by applying a seasonally coherent calibration to deterministic rainfall from the ACCESS-G NWP, combined with quantile mapping of other forcing variables, then running the AWRA-L model. Seasonal forecasts are being produced by running AWRA-L using ensemble forcing data from a dynamic seasonal forecasting system, ACCESS-S, bias-corrected to a 5km grid. Initial retrospective forecast skill analyses from both systems show useful skill across time-scales, seasons and locations. The Hydrological Projections project will produce national maps and data sets of the impacts of climate change on rainfall, runoff, soil moisture and evapotranspiration for decades to the century ahead. These will be produced by forcing AWRA-L with an ensemble of bias-corrected and downscaled GCMs.

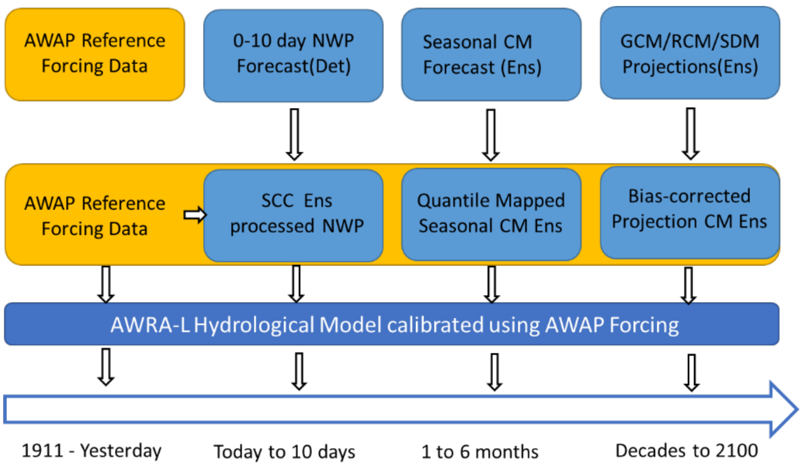

Fig 1. Overview of the soon to be released, expanded Australian Landscape Water Services

Once delivered, these new products will contribute towards comparable water services for the water, agriculture and other sectors, providing valuable, comparable data across time-scales, matching future predictions with the historical context. Future work could bring this into a truly seamless forecast system, by further developing post-processing methodologies and a water reanalysis.

Keywords: *Seamless, Hydrological projections, water resources modelling, hydrological forecasting,*

INVITED PAPER

EXTENDED ABSTRACT ONLY

Investigative verification: A case study of Australian Bureau of Meteorology precipitation forecasts

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Abstract: The Bureau of Meteorology forecasts daily rainfall out to a week in advance, as slices of a probability density function (e.g. chance of more than 1mm, 5mm and other thresholds). The Brier Score is a standard verification measure for any one of these forecasts, such as the chance of more than 1mm. The Ranked Probability Score is a standard verification measure for cumulative multi-category forecasts, combining forecasts for all thresholds in one score. The Bureau uses nation-wide summary values of the Ranked Probability Score and the Brier Score, and their associated skill scores, to track performance. Overall, when compared to a climatological reference forecast, the skill scores are around 0.5 when forecasting for tomorrow, decreasing to 0.1 when forecasting for 7 days in advance. These are compared to skill scores of 1 for a perfect forecast and 0 for a forecast without any skill.

However, a summary statistic is limited in the information it contains. By considering various stratifications of the data, and various verification techniques, we can test for conditional biases. Detailed investigation, presented in this study, has led to greater understanding and has led to changes in techniques resulting in improvements in the Bureau's forecasts.

For example, we detected over-forecasting of the chance of more than 1mm in the tropics but not the mid-latitudes. In the Tropics we found the biases were more pronounced at shorter lead days, with forecasts of 50% probability corresponding to rain events only 35% of the time. The Reliability component of the Brier Score for Summer 2017-18, shown in Figure 1, illustrates some of that information, and shows the substantial improvement achieved in 2018-19. This and other examples are presented as a case study of why one verification measure is insufficient, and as an example of how detailed examination of various verification metrics has led to improvements in the Bureau's rainfall forecasts.

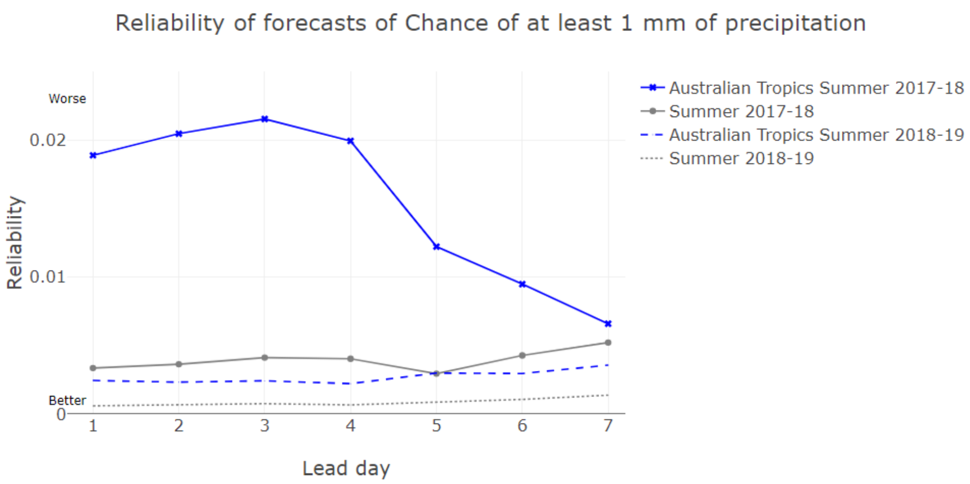

Figure 1. Reliability Component of the Brier Score for forecasts of at least 1mm of precipitation in a 24-hour period at lead times of 1 to 7 days. Lower values are better. Results show the Tropics (blue) contrasted to the whole of Australia (grey) for Summer 2017-18 (solid lines) and the improvement for Summer 2018-19 (dashed or dotted lines).

Keywords: *Verification, probabilistic forecasting, precipitation*

Daily hydrological forecasts forced with AWRA-L model on a continental scale

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Abstract: The Australian Bureau of Meteorology is currently working towards the release of a national system to provide high-resolution forecasts of root zone soil moisture, evapotranspiration and runoff. The proposed service will be based on the Australian Water Resources Assessment Landscape model (AWRA-L) and extends the functionality of the Australian Landscape Water Balance (www.bom.gov.au/water/landscape). The forecasts will have a maximum lead time of nine days, use a 5×5 km grid, and are based on climate inputs provided by the ACCESS-G numerical weather prediction model. This new prediction system will support flood watch and warnings, inform water resources operations, and provide a nationally consistent platform to manage catchment conditions. Forecast skill is assessed by comparing the forecasts with historical AWRA-L simulations forced with observed climate inputs (AWAP). Skill remains high and persists for most of the forecast lead time for evapotranspiration and soil moisture but diminishes sharply for runoff beyond 3 days' lead time. Unlike the other two variables – evapotranspiration and root zone soil moisture, the runoff deviates rapidly from the initial state and there is also undeniably significant impact from the quality of rainfall forecast. Skill assessment was further refined by comparing model outputs with runoff observations, and for specific catchments and flooding events. Future work will include direct assimilation of state variables to improve skill persistence.

Keywords: *Hydrological forecast, daily forecast, Continental scale, AWRA-L*

Forecasting monthly precipitation for the Han River basin in Korea using large scale climate teleconnections

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Abstract: Long-term forecasts of precipitation over a month to several months are important for dealing with droughts, floods, weather-related disasters, and securing and managing stable water resources. For this long-term forecast, studies using dynamic or statistical models have been conducted. This study utilized multiple regression models as a statistical approach to forecast monthly precipitation for the Han River basin in Korea. As a predictor, we used 39 global climate indices that are relatively constantly being updated, among the indices provided by NOAA on a monthly basis. For the month to forecast precipitation, high-correlated climate indices were selected from the correlations between global climate indices and observed precipitation over the past 30 years. And multiple regression models for predicting preceding precipitation were derived by combining the selected climate indices. In order to improve predictability, past precipitation data were used as a predictive factor and cross-validation was performed to select the optimal regression model group for each month. The prediction range was derived by using the predicted values from the regression model group and the predictability was evaluated by comparing with the actual observations.

We can predict monthly or seasonal rainfall up to 12 months in advance through the forecasting models, and also obtain the 3-category probability information (above normal, near normal, below normal) of the forecast results as provided by dynamic models. The forecast of monthly precipitation for 2010-2018 showed that predictability is good enough except for some summer period of typhoons or heavy rains. Especially, the predictability of spring, autumn and winter periods was relatively high, which was considered to be highly applicable to providing information for proactive response to drought and for securing water resources.

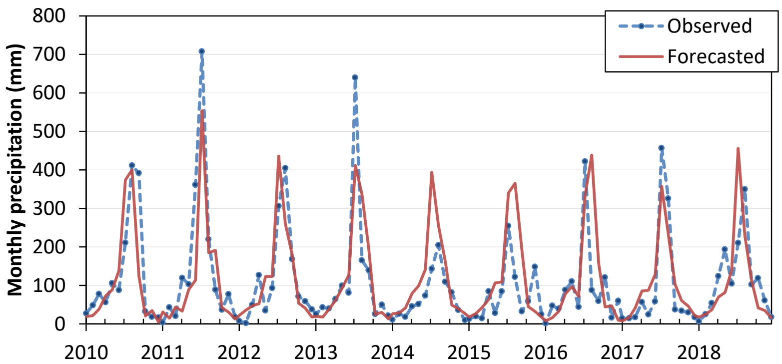

Figure 1. Comparison of observations and forecasts of monthly precipitation for 2010-2018 (6-month lead time)

Acknowledgement: This research was supported by a grant from a Strategic Research Project (20190151-001) funded by the Korea Institute of Civil Engineering and Building Technology.

Keywords: *Seasonal forecasting, climate index, multiple regression models*

Developing an artificial neural network model for predicting monthly rainfall in June for the Han River basin, Korea

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Abstract: An artificial neural network (ANN) model was constructed to predict the rainfall in June for the Han River basin using the global climate indices. The monthly global climate indices, obtained from the Climate Prediction Center of the National Oceanic and Atmospheric Administration, and the monthly rainfall data, provided by the National Water Resources Information System, were used as inputs and output of the ANN model. Candidates input variables for the ANN model were selected based on cross-correlation between the lagged climate index and June rainfall. The optimal input variables of the ANN model were finally determined using relative variable importance analysis during training.

Monte Carlo cross-validation (MCCV) was performed to estimate the prediction error and select the best ANN model with taking into account the uncertainty due to random sampling of the training data set and random initialization of weights between nodes. The neural network training was repeated 10,000 times using randomly sampled data and network weights. A total of 53 years data were randomly divided into three parts: 60% of the data for training, 20% for validation, and the remaining 20% for test data set. After 10,000 repetitions, the average of the predicted rainfall amounts for each training, validation and test was calculated and the performance was evaluated. The optimal neural network structure was selected based on the performance for test data set in the MCCV analysis.

The optimal ANN model with seven hidden nodes and eight input nodes - lagged climate indices such as Atlantic Meridional Mode (AMM(-12)), East Pacific/North Pacific Oscillation (EPNP(-2)), North Atlantic Oscillation (NAO(-6)), Scandinavia Pattern (SCAND(-3)), etc.,- was determined based on the MCCV results. The negative value in parentheses indicates the month of advance. The prediction errors have the RMSE of 42.9 mm, 44.2 mm, 60.1 mm, and the correlation coefficients of 0.885, 0.741, and 0.691 for training, validation, and test data sets, respectively. Figure 1 shows the 53 years of rainfall predictions for a combination of training, validation and test data sets. As can be seen in the figure, the ANN model showed acceptable results.

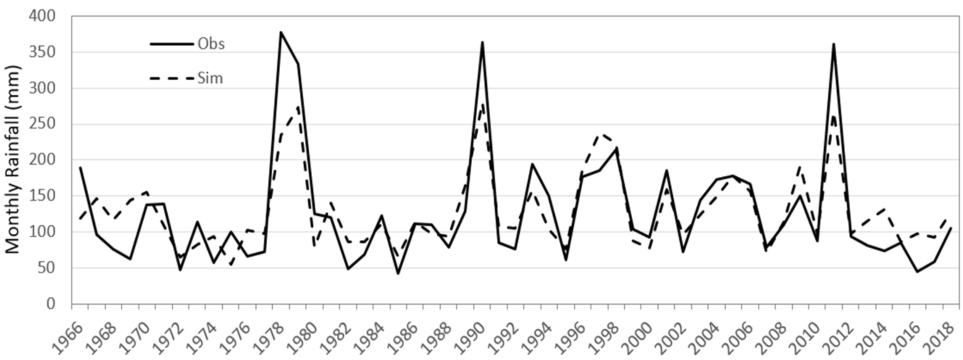

Figure 1. The comparison of observed and predicted monthly rainfall in June

Acknowledgments: This research was supported by a grant from a Strategic Research Project (20190151-001) funded by the Korea Institute of Civil Engineering and Building Technology.

Keywords: *Artificial neural network, global climate indices, Monte Carlo cross-validation*

EXTENDED ABSTRACT ONLY

Forecasting daily precipitation and temperature using spatial weather generator for watershed modelling in the Han River, Korea

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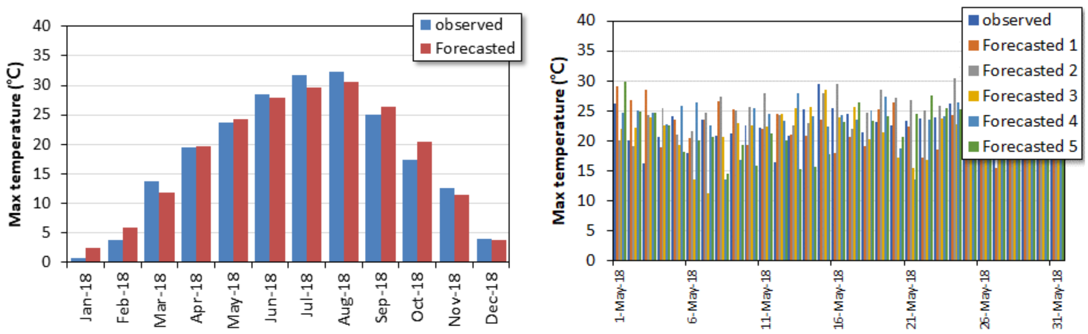
Abstract: Long-term forecasts of weather and streamflow is important for efficient water resource management. These long-term forecasts in the meteorological field are average meteorological information on monthly units and large scale basin. In the water resources field, long-term forecasts of streamflow using runoff models usually requires daily weather forecast inputs. Dynamical or statistical methods are used to produce these long-term weather forecasts and to downscale them in time and space. In this study, we aimed to downscale and evaluate information on monthly units and large scale basin into daily units and sites by using statistical methods to use weather forecast data as input data for runoff models.

Spatial and temporal downscaling of the Han River basin in Korea was performed according to the following procedure. Firstly, monthly long-term forecasts for precipitation and max/min temperature were produced using multiple regression analysis. Secondly, 3-category probability information (above normal, near normal, below normal) of the forecast results were obtained by comparing the results of 2400 regression models with historical data. Finally, as of December 2017, 500 sets of daily data based on the 3-category probability information were constructed for 2018 at each meteorological station using the spatial weather generator.

The monthly mean values of observation data and forecast data for each meteorological station were compared for 2018. In the case of temperature data, the forecast data was slightly underestimated, but the trend of observation data was well reproduced. In the case of precipitation data, further research is necessary. Uncertainty assessments for each step of forecasting, downscaling and runoff modelling should be performed to ensure reliability of long-term streamflow forecasting.



(a) Monthly forecasted (average of 500 sets) (b) Daily forecasted (5 cases from 500 sets)

Figure 1. The comparison of observations and forecasts of max temperature (Wonju station)

Acknowledgments: *This research was supported by a grant from a Strategic Research Project (20190151-001) funded by the Korea Institute of Civil Engineering and Building Technology.*

Keywords: *Downscaling, spatial weather generator, daily forecasting*

Potential benefits of rainfall forecast information and real-time control to reduce urban flooding using distributed smart stormwater storage systems

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Abstract: Urban flooding will require an investment in the order of $100s of millions per local government area to maintain current levels of service. The level of this investment is likely to increase in the future as a result of the impact of climate change, population growth and increased densification. While traditional investments aimed at increasing the capacity of stormwater systems have been directed towards pipe upgrades, there has been a growing focus on investments in storages as part of integrated urban water management initiatives, which enable the lifespan of existing stormwater systems to be extended. The use of storages for urban flood control also has a number of other advantages, such as the provision of water supply and the reduction in pollution levels in receiving waters.

Accurate rainfall forecasts can play a vital role in increasing the effectiveness of such storages. If forecasts of the timing and magnitude of impending rainfall events are available, storage outlet controls can be used to release stored water prior to a rainfall event to enable the expected runoff volume to be accommodated. If, additionally, forecasts of the temporal variation of impending rainfall events are available, storage outflows are able to be controlled in real-time during rainfall events by using formal optimisation methods. This enables runoff to be stored during more intense rainfall bursts to ensure the capacity of stormwater pipes is not exceeded, and stored water to be released during less intense rainfall periods, in readiness for subsequent increases in rainfall intensity. In addition, by jointly controlling the outflows from multiple, distributed storages, rather than using a single storage or controlling multiple storage independently, coincident flood peaks from different sub-catchments can be minimised, further reducing peak flows at critical locations.

In this study, the potential benefits of releasing stored water from distributed storages prior to a rainfall event and optimising the real-time release of water from these storages during a rainfall event are compared in terms of the storage volume required to achieve a certain level of peak flow reduction. The performance of these systems is also compared with a system that uses a single storage at the catchment outlet without flow controls, which is the most commonly used approach for peak flow reduction.

The above analyses are conducted for a case study based on a stormwater system in Unley, South Australia, which is fed by a catchment of approximately 36 ha, where the aim is to reduce peak stormwater flows by 31%. The stormwater system is modelled in the software package SWMM. The location, size and control of the storages are optimised using a multi-objective genetic algorithm. This is done over a range of design rainfall events, which are assumed to be known with certainty, therefore representing a best-case scenario. The results indicate that when the system of storages is controlled prior to the rainfall event based on perfect knowledge of the total rainfall amount, the storage volume required to achieve the desired peak flow reduction is only 56% of that required when a single, end-of system storage without control is used. When the system of storages is optimally controlled during a rainfall event based on perfect knowledge of the temporal variation of rainfall, this figure is reduced further to 21%. These results clearly demonstrate that the combination of optimal distributed storage optimal control based on known rainfall information has significant potential for extending the lifespan of existing stormwater systems, highlighting the importance and potential benefits of rainfall forecasts.

Keywords: *Smart stormwater, Real-time control, Low-impact development, Integrated urban water management, flood control, rainfall forecasts*

Integrated hydrologic forecasting-optimisation model to optimise reservoir release considering downstream flow target

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Abstract: Dam operators are tasked with deciding on the timing and magnitude of reservoir releases to best meet downstream water supply, ecological and other demands. In many cases however, the distance between reservoirs and water users complicates the problem with flow time-lags, tributary inflows and uncertainty in forecast rainfall. Here, we present an integrated hydrologic forecasting-optimisation model for optimising the release of a reservoir to achieve a predefined target flow downstream of the reservoir. The model comprises four major components: (i) a rainfall pre-processor for stochastic downscaling of numerical weather predictions, (ii) a hydrologic model, combining rainfall-runoff modelling and flow routing, to generate streamflow forecasts, (iii) a streamflow error model to reduce hydrological modelling errors and estimate uncertainty, and (iv) a nonlinear solver wrapped around the other model components to optimize the reservoir release. The model receives as input deterministic rainfall predictions for the next several days, the target flow, and the system initial conditions. The model yields the optimized reservoir release over the forecast horizon and an ensemble forecast of the streamflow at the target site given the optimized reservoir release. The model runs at an hourly time step. The optimisation constraints include an upper bound on the reservoir release, a limit on the change in the release from one time step to the next and the acceptable risk of exceeding a flow threshold at any location at any time. The model objective is to minimise the distance between the target flow and forecast flow. For this study, this distance is measured by the continuous rank probability score (CRPS). We apply the model to a section of the Murray River between Hume Dam and Lake Mulwala, which receives tributary inflows from the Ovens and Kiewa Rivers. We run the model iteratively, on a rolling basis, with 10-day-ahead rainfall forecasts from the Bureau of Meteorology's ACCESS-G weather model to optimise the release from Hume Dam given a target flow at the inlet to Lake Mulwala. Results are obtained for a 1-year period through 2011. The results show the optimised flow to match the target flow well, though there is a tendency for the optimised flow to overshoot the target in times of high natural flow. This is due to the streamflow forecasts underestimating during high flow periods, thus causing the integrated model to overestimate the required release from Hume Dam. Our work advances the use of ensemble streamflow forecasts in real-time water operation optimisation. It may be of interest to water managers seeking new ways to reduce risk and improve efficiency.

Keywords: *Reservoir operation, optimisation, hydrologic modelling, ensemble streamflow forecast*

Estimating Lake Mulwala Diversions for calibration of a semi-distributed hydrologic model of the Murray River

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Abstract: In hydrologic model calibration, storage diversions are often neglected due to the lack of sufficient data. While it may make little difference to include diversions where the points of interest are far downstream of the diversions, the same is not true where the distances between the former and latter are small. In this paper, we develop a series of equations using least squares optimisation to estimate the flow diversions from Lake Mulwala on the Murray River to Mulwala Canal in the north and Yarrawonga Main Channel in the south. We then use the equations to estimate the diversions for times when historical observations are unavailable. This is to provide data for calibrating a hydrologic model of the section of the Murray River between Hume Dam and Lake Mulwala. The hydrologic model is developed using the Short-term Water Information and Forecasting Tools (SWIFT2) and is intended for generating forecasts of the hourly inflow to Lake Mulwala when provided rainfall forecasts. The results show the equations to be most accurate when predicting the diversions in summer when the flows are highest, and when predicting the diversion to Mulwala Canal, the larger of the two diversions. Further, results of the calibration and validation performance of the hydrologic model show including the Lake Mulwala diversions (as opposed to neglecting them as is often the case where real data are unavailable) substantially improves the model fit, thus increasing the model credibility.

Keywords: *Storage diversions, hydrologic modelling, model calibration, SWIFT2*

Advances in seasonal streamflow forecasting provided by the Australian Bureau of Meteorology

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Abstract: The Bureau of Meteorology (Bureau) provides probabilistic hydrological (streamflow) forecasts to the public for 215 sites across Australia (www.bom.gov.au/water/ssf). Forecasts are generated using a statistical modeling method, relating antecedent catchment (streamflow) conditions and the observed climate state (climate indices) with the likely streamflow in the coming three months. Forecasts are issued every month. In parallel, a dynamic forecasting system was developed where seasonal rainfall forecasts from a general circulation model are forced through the GR4J rainfall-runoff model. This system was recently upgraded with (1) improved rainfall forecasts from the new ACCESS-S seasonal climate model now operated by the Bureau, (2) hydrologic scale pre-processing of rainfall forecasts with a statistical model and (3) improved streamflow post-processing.

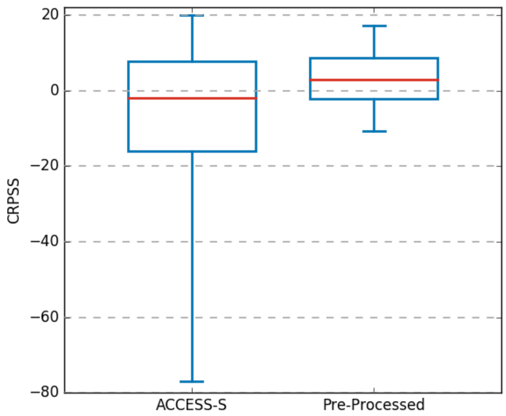

Figure 1. Skill-score distribution of rainfall forecasts (1 month ahead). Whiskers represent a 5%-95% interval

Forecast products were also enhanced with the provision of individual monthly totals out to three months. Additionally, a new merged product was developed combining statistical and dynamic forecasts into a single forecast ensemble product of individual monthly totals out to three months. This study presents the improved skill achieved through these different enhancements.

We apply a hydrological rainfall pre-processor to bias-correct raw rainfall forecasts and generate an ensemble range that ensures forecast reliability. The Cumulative Rank Probability Skill Score (CRPSS) distribution of ACCESS-S raw and pre-processed forecasts, issued every month between 1990-2012, across 516 catchments in Australia is provided in Figure 1. A clear reduction in negative skill-scores for total rainfall in the 1st month is evident, primarily due to a bias correction. Almost all pre-processed rainfall forecasts were found to be reliable.

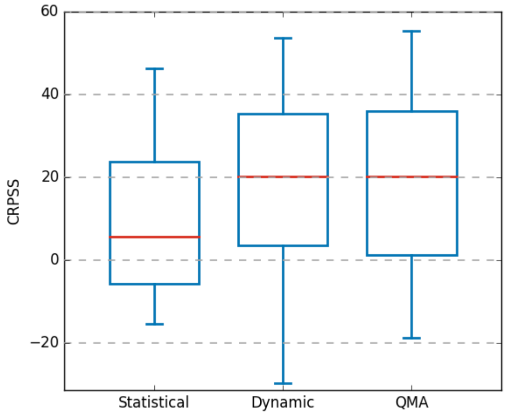

Figure 2. Skill-score distribution of streamflow forecasts (month 1).

Driven by the pre-processed seasonal rainfall forecasts, the dynamic modelling method runs a calibrated GR4J model to provide daily streamflow forecasts out to 90 days. Aggregated monthly streamflow forecasts are then post-processed with an autoregressive model. These forecasts are then merged with statistical forecasts by applying the quantile model averaging (QMA) method. Figure 2 provides the range in CRPSS across 209 catchments for the statistical, dynamic and merged forecasts for the first month of the 3-month forecast. A clear improvement in forecast skill with QMA is evident over the individual statistical or dynamic methods. In most cases, QMA places higher weight to the dynamic model but in certain cases, it favors the statistical model (note the wider distribution spread of the dynamic model relative to the statistical model). Almost all QMA forecasts are reliable. A detailed spatial and temporal/seasonal analysis of forecast skill using many skill metrics was completed as part of this study.

Keywords: *Seasonal streamflow forecasting, hydrological rainfall pre-processing, hydrological modeling, hydrological forecasting*

Verifying ensemble forecasts where observations are modeled output: a case study of soil moisture

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Abstract: Forecasts at time scales of hours to seasons are valuable for a range of operational decision-making applications. Characterizing forecast performance through verification is a critical step in establishing user confidence. Forecast verification involves comparing forecasts to corresponding observations and computing scores that characterize desirable properties of forecasts. Forecasts are often made for variables that are directly observable, such as streamflow, temperature, and rainfall. However, there are also many examples where forecast variables are not directly observable. In these instances, forecasts are often verified against model-derived observations, which are generated by running models with assumed 'true' forcings. Measured observations can have very different characteristics to model-derived observations. In this study we show that model-derived observations can confound existing forecast verification strategies.

A key property of ensemble forecasts is reliability. Reliability assesses whether the ensembles are too narrow or too wide, and also whether probabilities derived from the ensemble are meaningful. A common and rigorous test of reliability is to check the uniformity of Probability Integral Transforms (PIT). To calculate a PIT for each forecast, a cumulative distribution function (CDF), F, is derived for the forecast ensemble. The PIT is the the probability of the observation, x, in the CDF, given by $F(x)$. For the PIT values of many forecasts to be uniformly distributed, observations cannot consistently fall in one part of the ensemble: for example, forecasts are not reliable if observations continually fall near the bottom edge of (or outside) the ensemble.

In this case study we are concerned with ensemble forecasts of soil moisture. Soil moisture is modelled using an Antecedent Precipitation Index (API) model that is forced by precipitation and assumes a seasonally-varying decay factor. The decay factor is analgous to soil moisture depletion by seasonally-varying climatological potential evapotranspiration. We generate ensemble soil moisture forecasts for lead times to 10 days by forcing the initialized API model with ensemble precipitation forecasts generated by calibrating rainfall forecasts. As direct observations of soil moisture are not available, we verify forecast reliability using simulations generated by forcing the API model with observed precipitation.

The use of model-derived observations presents a major challenge in assessing the reliability of ensemble forecasts of soil moisture. Both the soil moisture forecasts and model-derived observations used for verification have a lower bound that varies in time. The bound arises when the API model is forced with zero precipitation, and the value of the bound depends on the soil moisture state at the previous time step. When this occurs, a forecast ensemble can display a point mass at the lower bound which requires explicit treatment when calculating PIT values. When observed soil moisture falls on the lower bound we generated a pseudo-PIT value to account for the point mass in the forecast distribution. This approach is analogous to the pseudo-PIT treatment given to zero-valued rainfall or streamflow forecasts, but the lower bound is time-varying.

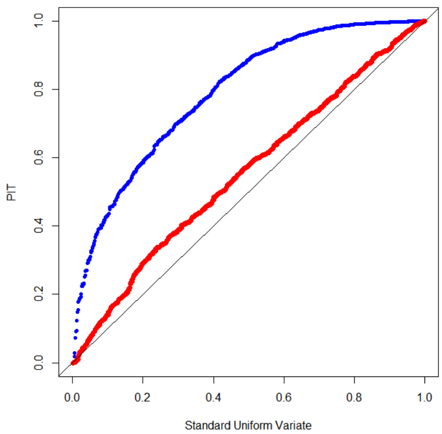

Figure 1. PIT-uniform probability plot generated without (blue) and with (red) considering the time-varying lower bound on soil moisture. Reliable forecasts fall on the diagonal

Time-varying bounds on forecast probability distributions can occur in a range of ensemble forecast verification problems, and are particularly evident where observations are model-derived. Our method allows the formal assessment of reliability in such cases, which was not previously possible.

Keywords: *Forecast verification, ensemble forecasts, soil moisture, reliability, probability integral transform*

Embedding trend into seasonal temperature forecasts through statistical calibration of GCM outputs

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Abstract: Skillful and reliable seasonal climate forecasts are often sought by industries and governments to support decision making under climate variability and change. The land surface temperature has exhibited temporal trends regionally and globally since decades ago. However, such trend is generally underestimated by seasonal temperature forecasts produced by coupled general circulation models (GCMs). Current statistical calibration methods mostly attempt to reduce bias and correct ensemble spread of raw forecasts, but seldom embed trend in calibrated forecasts. As a result, the calibrated forecasts also fail to capture observed temperature trend. Addressing this problem will raise user confidence in seasonal temperature forecasts.

This work extends the Bayesian joint probability (BJP) modelling approach for statistical calibration. The original BJP model formulates the relationship between the raw GCM ensemble means and observations via a joint probability distribution. Here, a trend component is introduced into the BJP algorithm for embedding observed trend into calibrated ensemble forecasts. The new model, named BJP-t, is applied to case studies for January mean maximum temperature in Australia. We calibrate and evaluate the 36-year reforecasts from the SEAS5 model, operated by the European Centre for Medium-Range Weather Forecasts (ECMWF), at one-month lead-time. We compare the performance of the BJP-t calibrated ensemble forecasts to the mean-corrected raw ensemble forecasts and the BJP calibrated forecasts using a leave-one-year-out cross validation setup.

The results show that the BJP-t calibrated ensemble forecasts can reproduce the observed trend when both the raw ensemble forecasts and the BJP calibrated ensemble forecasts do not sufficiently represent such trend (Figure 1). The BJP-t calibration is effective in making forecasts more skillful, more reliable and sharper than the BJP calibration, indicating that the BJP-t calibrated forecasts are more suitable for practical use. Further work includes adapting the BJP-t model to other climate variables, such as precipitation.

Keywords: *Seasonal temperature forecast calibration, climate trend, forecast skill, reliability and sharpness*

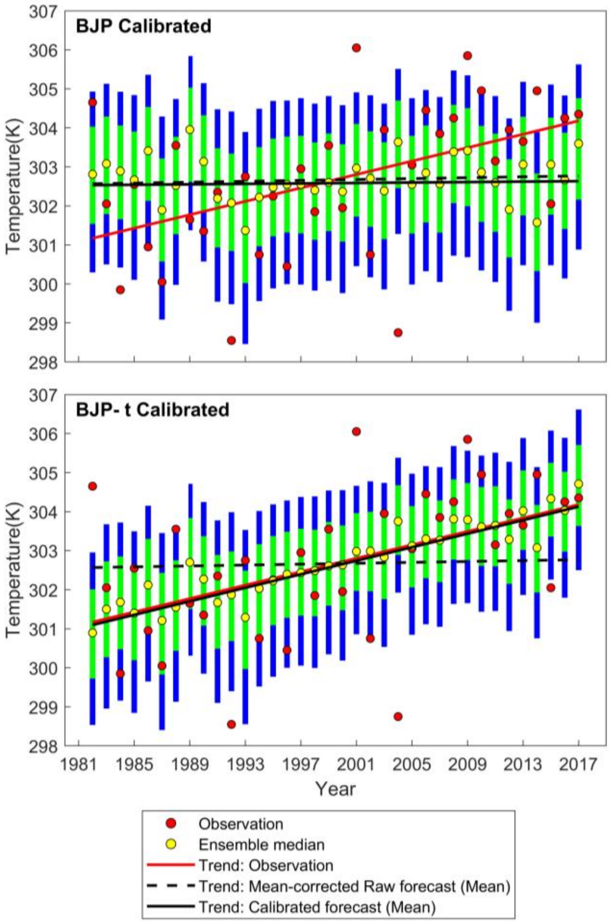

Figure 1: Forecast quantiles, mean-corrected raw forecast means, and observed values plotted for the BJP calibrated forecasts (top) and the BJP-t calibrated forecasts (bottom) in one case

EXTENDED ABSTRACT ONLY

Towards hydrological pre-processing of numerical weather predictions for multiple issue time initializations

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Abstract: Advances in computing power and data assimilation techniques have enabled numerical weather prediction (NWP) models to issue forecasts multiple times in a day. However, these forecasts still contain systematic errors that limit their value for hydrological applications, particularly for flood forecasting. In order to reduce such errors, previously we have developed catchment-scale hydrologic pre-processing of precipitation forecasts (CHyPP). CHyPP is based on the Bayesian joint probability (BJP) model, which was originally developed for seasonal streamflow forecasting, and the Schaake shuffle. The BJP relates rainfall forecasts and observations by modelling their joint distribution to correct biases and to quantify uncertainty (referred to as calibration). The Schaake shuffle ensures realistic space-time patterns in the calibrated forecasts. Originally, a separate CHyPP model was developed for each lead-time and location independently. Recent work increased the robustness of the CHyPP by introducing a parsimonious lead-time dependent parameterization and full Bayesian inference. The lead-time dependent parameterization characterizes discrepancies in the diurnal cycles of observed and forecast precipitation.

The lead-time dependent parameterization of CHyPP has been formulated to calibrate forecasts issued at a single time each day to match the needs of the Bureau's 7-day ensemble streamflow forecasts that are updated only once per day. However, streamflow forecasts generated to support flood warnings are updated multiple times each day. Therefore, it is critical to calibrate rainfall forecasts issued at multiple times per day. For an operational forecaster, it is convenient to have a single CHyPP model that can be employed to generate forecasts for multiple issues time rather than to have multiple CHyPP models for each issue time.

In this study we extend CHyPP parameterization to calibrate rainfall forecasts issued at multiple times per day. We apply the method to the catchment-scale rainfall forecasts from ACCESS-G NWP in 9 Australian catchments that cover a wide range of sizes, climatic conditions and hydrological characteristics. We use forecasts initialized at 00:00 Z and 12:00 Z. We find that CHyPP parameters inferred using forecasts issued multiple times each day are similar to those inferred using a single issue time. We demonstrate that the calibrated forecasts generated using multiple issue time parameterization are of equivalent quality to those generated by single issue time parameterization. However, computational resource required and the number of parameters to be inferred for the new parameterization is significantly smaller than that required for single issue time parameterization, this is critical for real time application of the CHyPP, particularly for floods and high flow events.

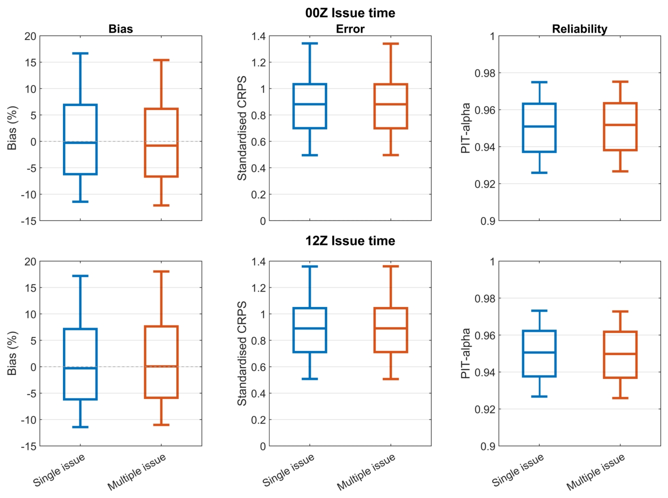

Figure 1. Verification scores of calibrated rainfall forecasts when parameters are inferred using single (blue color) and multiple (red) issue times. Boxes show interquartile range and median, whiskers show 10th and 90th percentiles. Box plots for each score are computed by pooling the verification scores of all subareas and lead times of 9 catchments.

Keywords: *CHyPP, rainfall forecasts, hydrological pre-processing, numerical weather prediction*

Postprocessing and skill assessment of AWRA seasonal runoff forecasts at key locations across Australia

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Abstract: AWRA seasonal runoff forecasts are currently generated by forcing the AWRA-L model with ACCESS-S climate forecasts (bias-corrected by quantile mapping). At a continental scale, these runoff forecasts exhibit a sensible spatial and temporal pattern. However, it is expected that there is considerable scope to improve the runoff forecasts through calibration against observed runoff at a local scale.

In this work, we aim to post-process AWRA seasonal runoff forecasts to remove local scale bias and produce ensemble forecasts and skill metrics. A total of 50 sites are selected across Australia. AWRA-L v5 monthly output (ensemble mean) for the period 1990-2012 and the gauged runoff for the same period of each site are provided by Bureau of Meteorology. The Bayesian joint probability model with the Gibbs sampling algorithm (BJP_g) is applied to each site and each month to calibrate the AWRA monthly forecasts at lead time 0 based on the runoff observations. Two predictors: (1) the last monthly runoff observation; and (2) monthly forecast mean streamflow for lead 0, and one predictand of the observed streamflow of the current month are considered. The probabilistic post-processed monthly runoff forecasts with 3000 ensemble members are generated. The probabilistic climatology forecasts using the same statistical model are also generated for evaluation.

We evaluate the model performance based on the skill metrics such as the continuous ranked probability score CRPS (Fig 1), the Kolmogorov – Smirnov (KS) statistics, the quantile range and the bias. The CRPS skill scores of the calibrated ensemble forecasts significantly improved compared with the raw forecasts, with the median of the CRPS skill score about 20-40%. Results from KS test and quantile range show reliable calibrated forecasts and reduced uncertainty. The bias is largely reduced for the calibrated ensemble forecasts. The BJP_g calibrated forecasts are found to be reliable in ensemble spread.

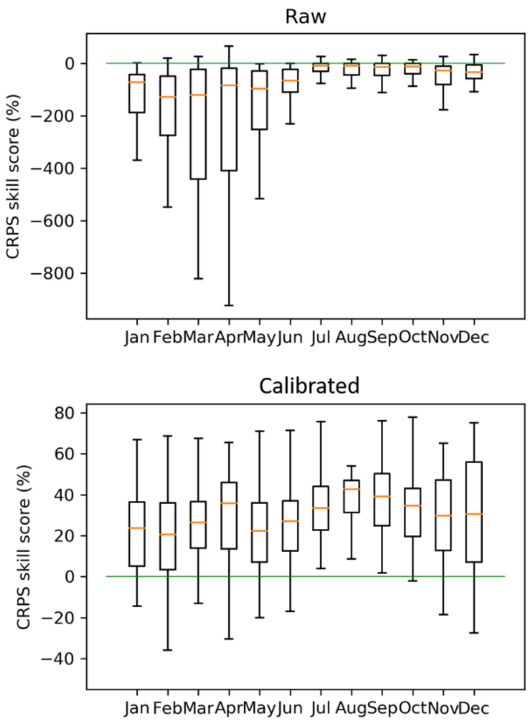

Figure 1. The CRPS skill scores of raw forecasts (top) and calibrated ensemble forecasts (bottom)

Keywords: *Seasonal runoff forecasts, ensemble forecasting, statistical calibration, AWRA-L*

GLOFFIS: the Deltares global hydrological forecasting system

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Abstract: Deltares operates a real-time fluvial forecasting system with global coverage: the Global Flood Forecasting and Information System (GLOFFIS). The system produces estimates of various hydrological parameters at any location in the world for both the recent past and the near future.

The continued investment in GLOFFIS is justified by various reasons. Primarily, there is an R&D rationale. Any operational system that runs in near real-time poses high requirements to the availability of input data and the runtime of the models used. This problem is augmented when applying the system to the global scale: both model domains and data volumes become significantly larger. Also, data originates from a wide variety of sources. Runtimes, however, cannot be significantly larger hence this poses additional requirements to the efficiency of models used. Solving these issues requires a considerable R&D effort. The resulting developments tend to be useful for the 'local' systems we develop and maintain for our clients. An additional rationale is found in the increased demand for global forecasts – notably from a client base that is not able or willing to operate forecasting systems themselves.

At its core, GLOFFIS operates a set of hydrological models that, jointly, cover the entire earth's land. The models are forced by meteorological data – pertaining to both the recent past and the near future. The models produce estimates of various hydrological parameters such as soil moisture content, surface water runoff and streamflow rates. Future versions of GLOFFIS will include hydrodynamic models, allowing to produce estimates of water level in addition to streamflow rates. Also, future versions will include seasonal forecasts, i.e. forecasts going out several weeks if not months. In addition to real-time data, the system enables the production of long-term timeseries.

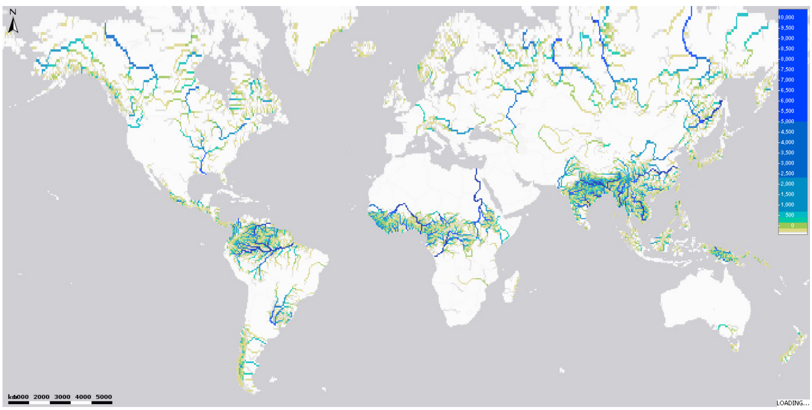

Figure 1. Illustrative example of the models contained in GLOFFIS. This particular -very coarse- model is used for demonstration purposes only. The – more useful – models have a spatial resolution of 1km by 1km.

In terms of the infrastructure of the system, GLOFFIS is based on the Delft-FEWS forecast production system and on the wflow framework for hydrological modelling. Neither of these require any licensing fees and the latter is available through an open source license. The Delft-FEWS system is used for many operational flood forecasting systems including those of the Bureau of Meteorology and many other national forecasting agencies. Wflow is a distributed modelling framework specifically designed to accommodate multiple model schematization types and data assimilation techniques. For GLOFFIS, we opted for the physically based wflow_sbm that uses kinematic wave routing for surface and subsurface flow. Through the application of so-called pedotransfer functions that translate input base maps to model parameter values using upscaling rules that ensure flux-matching, these require little calibration.

Some GLOFFIS outputs are available through www.globalfloodforecast.com although most users will retrieve their data through bespoke data transfer mechanisms.

Keywords: *Realtime hydrological forecasting, global hydrological models, forecast informed decision making*

Seasonal hydrological forecasts for Australia using ACCESS-S1 and the AWRA-L water balance model

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Abstract: The Bureau of Meteorology (BoM) provides seasonal outlooks of precipitation and temperature across Australia (using the ACCESS-S1 modelling system) and predictions of streamflow at select locations, several months in advance. Similar forecasts of hydrological variables across all of Australia could offer benefits to many sectors, including water resources management, food production and flood and bushfire risk assessments. Here, we present the development and testing of a seasonal forecasting system for soil moisture, evapotranspiration and runoff for Australia using the AWRA landscape water balance model (AWRA-L), forced with climate outputs of the Australian Community Climate and Earth-System Simulator – Seasonal (ACCESS-S).

ACCESS-S is a general circulation model and underpins the seasonal forecasting system of the BoM. It recently replaced the previous system, POAMA (Hudson et al. 2013) and offers a range of improvements – most notably higher horizontal and vertical resolutions and up-to-date parameterisations of physical processes. These upgrades improved the representation of topographic features, large-scale climate drivers (such as ENSO) and regional climate. ACCESS-S outputs were regridded to a 0.05° resolution using bilinear interpolation and bias-corrected using quantile mapping (Griffiths et al. 2017) to produce climate data of the same resolution and statistical properties (mean and variance) as the Bureau's historical AWAP climate dataset (Jones, Wang and Fawcett, 2009).

We forced the Bureau's gridded landscape water balance model AWRA-L (Frost, Ramchurn, and Smith 2016; Viney et al. 2015; available via https://github.com/awracms/awra_cms) with the interpolated and bias-corrected ACCESS-S hindcasts of daily precipitation, minimum and maximum air temperature, and solar radiation. AWRA-L was developed by CSIRO and BoM and underpins the Australian Landscape Water Balance website (www.bom.gov.au/water/landscape), providing information on Australia's water resources covering the period 1911 until yesterday. The model simulates hydrological fluxes and stores, including runoff, evapotranspiration and soil moisture for three soil layers (0-0.1m, 0.1-1m, 1-6m), on a 5 km grid. AWRA-L model v5 used here is calibrated to catchment streamflow and satellite soil moisture and evapotranspiration (Frost, Ramchurn, and Smith 2016) and was extensively evaluated against available hydrological observations (Frost, Ramchurn, and Hafeez 2016). AWRA-L performs well overall for the water balance and was therefore selected for use here.

Forcing AWRA-L with ACCESS-S climate outputs, we produced hindcasts of root-zone soil moisture (0-1m), evapotranspiration and runoff for the years 1990-2012 (starting on the 1st of each month). Each hindcast has a length of 217 days and consists of 11 ensemble members. The daily output was aggregated to the monthly scale. Here, we present the results of the assessment of the forecast performance against a historical AWRA-L reference run forced with AWAP data. We applied verification metrics for deterministic and ensemble forecasts that capture the accuracy and reliability of the forecasts (including mean bias, anomaly correlation, CRPS) for mean conditions and percentile-based thresholds. Subsequently, we discuss sources of skill by presenting comparisons with three reference forecasts – persistence, a climatology ensemble forecast and an initial states ensemble forecast.

Keywords: *Seasonal forecasting, drought, flood, risk assessment*

Processing numerical weather prediction (NWP) outputs to enhance precipitation forecasting for Australia

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Abstract: Statistical processing of raw forecasts from NWP models aims to produce forecasts that are unbiased, reliable in ensemble spread, as skillful as possible and consistent with seasonally varying climatology. However, many processing models are inadequate in representing the seasonality of precipitation, resulting in unrealistic forecasts especially for regions with strong seasonality. This problem is often caused by the availability of only short archives of NWP data for establishing statistical calibration models. In this study, we implement the newly developed seasonally coherent calibration (SCC) model and the Schaake shuffle technique to improve precipitation forecasts across Australia.

The SCC model has been developed to resolve three key issues: (1) constructing a calibration model that is sophisticated enough to allow for seasonal variation in the statistical characteristics of raw forecasts and observations, (2) bringing climatology that is representative of long-term statistics into the calibration model, and (3) reducing the number of model parameters through sensible re-parameterisation to make the model workable with short NWP datasets.

In our implementation, we process the precipitation forecasts produced by the Australian Community Climate and Earth-System Simulator (ACCESS-G2) model. As an operational model of the Australian Government Bureau of Meteorology, ACCESS-G2 provides weather forecasts for 10 days ahead. We process raw precipitation forecasts in reference to the Australian Water Availability Project (AWAP) precipitation data during April 2016-March 2018. Specifically, we first apply the SCC model to individual grid cells (with a spatial resolution of 5km) and lead-times to generate calibrated ensemble forecasts across Australia. The Schaake shuffle technique is then applied to link ensemble members of the calibrated forecasts across grid cells and over lead-times, so that the forecast ensemble members are coherent in spatial and temporal patterns.

The quality of the calibrated forecasts is assessed by evaluating bias, accuracy, reliability in ensemble spread, and percentage of wet days. The spatial and temporal patterns instilled by the Schaake shuffle are assessed by evaluating reliability in ensemble spread when aggregated to coarser spatial and temporal scales. The SCC calibrated forecasts are found to produce significant improvements over raw forecasts. The shuffled ensemble forecasts are shown to be reliable at various spatial and temporal scales, indicating that the forecast ensemble members have realistic spatial and temporal patterns.

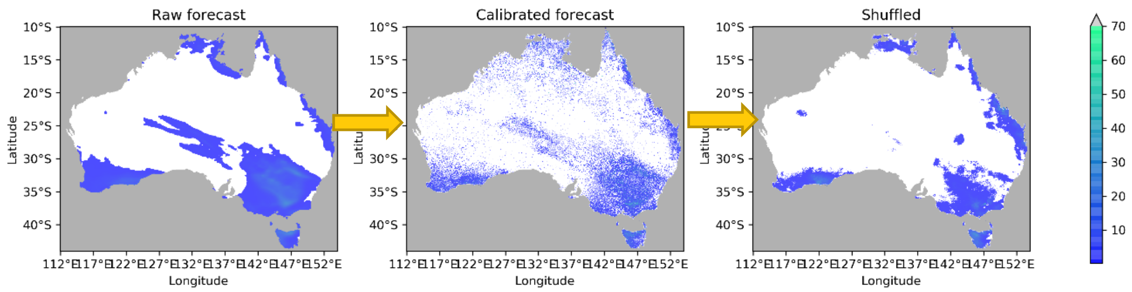

Figure 1. Precipitation processing with SCC and Schaake shuffle

The processing methods can be easily adapted for applications to future operational NWP models. The methodology will also be applicable to other NWP variables, such as temperature, wind, vapor pressure, solar radiation, and reference crop evapotranspiration, which are also of interests to many forecast users. The processing will benefit a broad range of forecast users by providing well-calibrated ensemble forecasts in high-resolution across Australia.

Keywords: *Statistical calibration, ensemble weather forecasts, climatology, seasonality, Schaake shuffle*

Improving Numerical Weather Prediction (NWP) forecasts for Australia using a quantile mapping method

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Abstract: Systematic errors in Numerical Weather Prediction (NWP) forecasts resulting from inaccuracies in model initialization and representation of physical processes necessitate the application of statistical models to correct raw forecasts. Sophisticated methods with divergent structures have been developed to calibrate NWP forecasts. Due to the complex optimization of parameters in applying these methods, their implementation is often computationally expensive, particularly when processing forecasts at the continental scale. For the processing of precipitation forecasts across Australia, we implemented a sophisticated Seasonally Coherent Calibration (SCC) model to generate calibrated ensemble forecasts. To develop a complete set of weather forcings for water balance forecasting using the Australian Water Resource Assessment (AWRA) model, we need to correct NWP forecasts of five additional weather variables for Australia. While it is possible to process these variables using SCC style models to generate ensemble forecasts, the computation effort and data storage required is considerable. As a first step, it is decided that only deterministic bias-corrections are made to the raw NWP forecasts.

In this study, we employ a quantile mapping (QUANT) method to process forecasts of multiple weather variables (maximum daily temperature, minimum daily temperature, solar radiation, wind speed, and vapor pressure) produced by the Australian Community Climate and Earth-System Simulator (ACCESS-G2). Effective bias-correction with the QUANT method relies on well-developed empirical cumulative distribution functions that characterize the full range and seasonal pattern of the selected variables. It is problematic to apply this method directly to archived raw forecasts shorter than one annual cycle, a situation often encountered when NWP models first become operational. To overcome this problem, we subtract the observed daily long-term climatological means from raw forecasts of the five variables, and apply QUANT to bias-correct anomalies. Then the climatological means are added back to the anomalies after bias-corrections to generate bias-corrected forecasts.

Bias-corrected forecasts are evaluated against reference data (AWAP; Jones et al, 2009; McVicar et al, 2008). The Continuous Ranked Probability Score (CRPS) is used to measure improvement in forecasting skill. Results demonstrate substantial reductions in forecast bias. For each of the five variables, widespread underestimation or overestimation is effectively corrected, and bias in the processed forecasts across different parts of Australia is close to zero. Bias-corrected forecasts have considerably higher CRPS skill score than the raw forecasts.

As a critical component of terrestrial water cycle, evapotranspiration is closely related to the five variables, and thus could serve as a surrogate indicator for evaluation. We examine the overall effectiveness of the bias-correction by comparing the reference crop evapotranspiration (ETo) calculated based on the raw and individually corrected variables. ETo forecasts calculated with the individually corrected variables present substantially lower bias and higher CRPS skill score relative to estimates based on raw forecasts.

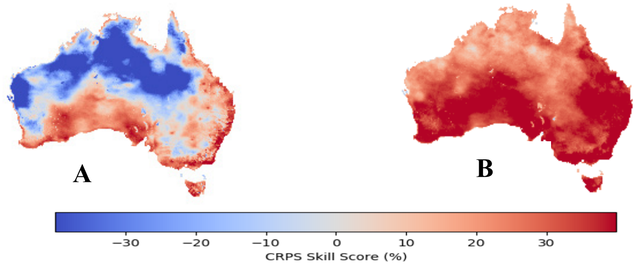

Figure 1. CRPS skill score of the ETo estimates based on (A) raw and (B) bias-corrected forecasts

Keywords: *Statistical calibration, bias-correction, quantile mapping, climatological mean*

Gradient boosting machine assisted approximate Bayesian computation for uncertainty analysis of rainfall-runoff model parameters

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Abstract: Bayesian inference is a well-regarded approach for diagnostic model evaluation that is often applied to hydrological models to constrain parameters and estimate uncertainty within a statistical framework. Typically, Bayesian uncertainty analysis is carried out using the Generalised Likelihood Uncertainty Estimation (GLUE) or Markov Chain Monte Carlo (MCMC) sampling. Approximate Bayesian Computation (ABC) is alternative set of likelihood-free Bayesian methods that have been gathering interest in many fields including astrophysics, population genetics and biology.

The main appeal of ABC is that is the requirement for a formal likelihood function is replaced by one or more summary statistics that compare the simulated model to the observed data. ABC works in situations where an analytical likelihood function is either unavailable or intractable. Instead of evaluating the likelihood function, ABC only has to be able to sample from the likelihood function in an empirical fashion. This broadens the class of problems to which statistical inference can be applied.

In practice, the appeal of the ABC method is limited somewhat due to its requirement for a large number of model evaluations. Because ABC is essentially a rejection sampling method, when the overlap between the prior and the posterior is poor, the sampling efficiency can be very low and it may be necessary for hundreds of thousands or even millions of model evaluations to be run to collect an appropriate number of accepted samples to construct a statistically informative posterior. If the model runtime is significant, ABC rejection sampling can easily be rendered impractical. In this paper a hybrid method is developed that serves to retain the flexibility of ABC while drastically reducing the computational effort required. The first component of the hybrid approach is to employ Sequential Monte Carlo sampling (SMC) to improve the sampling efficiency and reduce the total number of samples required. Secondly, the primitive model is replaced by a surrogate model that can accurately reproduce the results of the original model at a fraction of the computational cost. In this case, XGBoost, a gradient boosted regression tree machine learning algorithm, is used to construct the surrogate models.

Employed together, SMC-ABC and XGBoost trained surrogate models offer an accurate and efficient framework for model parameter inference and uncertainty analysis. As a demonstration, the proposed method is applied to a four parameter GR4J distributed rainfall runoff model to estimate marginal model parameter probability density functions for parameter identification and uncertainty analysis.

Keywords: *Uncertainty analysis, conceptual model, Bayesian inference*

Reliable predictive uncertainty distributions in rivers with >50% zero flow

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Abstract: Flow simulations of ephemeral rivers are often highly uncertain. Therefore, error models that can reliably quantify predictive uncertainty are particularly important. Error models usually predict errors by randomly sampling from a distribution centred on the hydrological model simulation. That is, errors are assigned a ~50% probabilility of falling above the simulation. Because flow cannot fall below zero, such error models can predict at most 50% of zero flow. This renders reliable predictive distributions impossible for highly ephemeral rivers with >50% zero flow.

We propose a new method to produce reliable predictions in highly ephemeral rivers. The method fits a data transformation to observed flow. After observations and simulations have been transformed, we assume residuals are normally distributed. Parameters of the hydrological and error model are then estimated by maximum likelihood estimation. Initially, we assume both observed (q) and simulated ($\tilde{q}$) flow can equal zero. The likelihood has to consider four cases:

1. $case = 1$ when both $q(t) > 0$ and $\tilde{q}(t) > 0$;
2. $case = 2$ when $q(t) = 0$ but $\tilde{q}(t) > 0$;
3. $case = 3$ when $q(t) > 0$ and $\tilde{q}(t) = 0$;
4. $case = 4$ when both $q(t) = 0$ and $\tilde{q}(t) = 0$.

In cases 2-4, our assumption of normally distributed residuals breaks down. To handle these cases, we treat both observed and simulated flows as censored data in the likelihood.

Once we have a set of parameters, we generate simulations with predictive uncertainty. When the simulation $\tilde{q}(t) = 0$, we replace the transformed value of zero with a random number less than or equal to the transformed value of zero. We then add uncertainty by sampling from our normal predictive distribution, as usual. This process allows the median of the predictive distribution to drop below the transformed value of zero, enabling predictive distributions with >50% zero flow. Transformed predictions below the transformed value of zero are converted to zero in the q domain as part of the back-transformation.

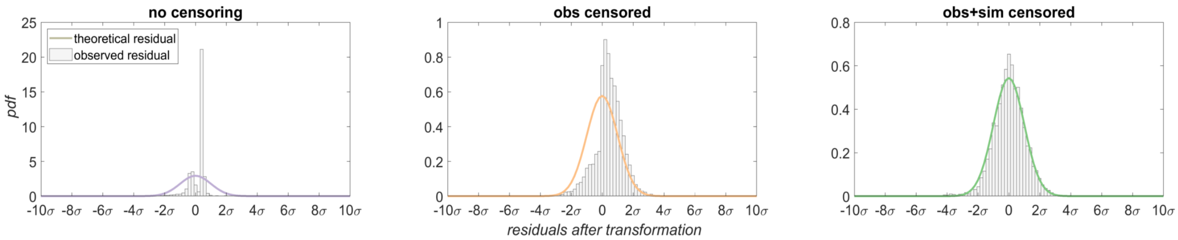

Figure 1. Theoretical (lines) and actual (histograms) distributions of residuals after transformation for the Fletcher River (WA), where 69% of observed flow is zero. Left panel: error model fitted without censoring; centre panel: error model fitted by censoring only observations; right panel: our new method. Only our new method produces normal residuals.

Handling cases where $\tilde{q}(t) = 0$ has limited practical application, because many conceptual hydrological models do not produce zero flow. Because of this, we broaden our method to handle general censoring thresholds, which can be greater than zero. We show that our method is capable of producing reliable predictions in even highly ephemeral rivers with >50% zero flow. Our new method allows, for the first time, reliable predictions to be generated for all rivers, regardless of the degree of ephemerality.

Keywords: *Predictive uncertainty, ephemeral rivers, data censoring, maximum likelihood estimation*

Resolving transboundary water conflict by the game model considering inflow forecasting errors

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Abstract: Conflicts often arise when different water users compete for a limited water supply. Resolving transboundary water conflict is an important task for water resources management in river basins. This study takes watershed management agency as the leader, the associated catchment area as the follower, and proposes a two-level asymmetric Nash-Harsanyi Leader-Follower game model while considering errors in the inflow forecast used to inform the water allocation. In the proposed model, we use a Monte Carlo method to analyze the uncertainty of various stakeholder's allocation results and also the response regularity to the available water resource uncertainty. We then establish a quantitative relationship between the allocation results of stakeholders and the mean and standard deviation of the available water resource. The Huaihe River basin in China is selected as a case study. The contradiction between supply and demand in the Huaihe River basin is prominent, and inter-provincial water resources allocation conflicts have become a serious problem. In the case study, the watershed management agency serves as the leader, three provinces (Henan, Anhui and Jiangsu) serve as followers. The results show that: (1) the water allocated to the watershed management agency and three provinces (Henan, Anhui and Jiangsu) also has a normal distribution when the inflow forecasting error obey a normal distribution; (2) the sum of the mean of the water allocated to stakeholders equals the mean of the forecasted available water, and the sum of the standard deviation of the water allocated to stakeholders equals the standard deviation of the forecasted available water; (3) the mean and standard deviation of the allocation results have a good linear relationship with the mean and standard deviation of the forecasted available water; (4) the stakeholders' distribution parameters can be directly derived from the distribution parameters of the forecast information, which will help stakeholders to make decisions and improve the practical value of the method.

Keywords: *Inflow forecasting errors, a two-level asymmetric Nash-Harsanyi Leader-Follower game model, quantitative relationship, uncertainty*

Error propagation in coupled hydrologic-hydraulic modelling of floods at the large scale

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Abstract: Flood modelling at the regional to global scale is a key requirement for equitable emergency and land management. Coupled hydrological-hydraulic models are at the core of flood forecasting and risk assessment models. Nevertheless, each model is subject to uncertainties from different sources (e.g., model structure, parameters, and inputs). Improving the understanding of the propagation of these uncertainties through the modelling cascade is essential to pinpoint strategies to enhance model accuracy and comprehensively communicate modelling results to end users. However, a rigorous assessment requires identification of all the sources of uncertainty and results in a large number of model runs with extremely high computational costs, especially when using distributed models. Consequently, this study focused on one source of uncertainty. Specifically, this study investigated the impact of discrepancies between simulated and measured time series of discharge data for the prediction of long-term patterns of floodplain inundation volumes and extents.

This objective was achieved using a numerical experiment based on a state-of-the-art modelling framework. In this experimental design, two input time series were used to represent the discrepancies between modelled and measured discharge hydrographs in a real forecasting scenario. The coupled modelling chain consisted of two widely used models, that is the hydrological model Hydrologiska Byråns Vattenbalansavdelning (HBV) and the hydraulic model LISFLOOD-FP. The case study was the Murray Darling Basin (Australia). Simulated and measured discharge time series were alternatively used as input to the hydraulic model for the prediction of floodplain inundation volumes and extents from 2006 to 2012.

A novel quantitative methodology was used to (1) investigate whether discrepancies in input time series are enhanced or damped by the hydraulic model for the prediction of floodplain inundation volumes and extents; (2) identify causes for such effects; (3) investigate whether continuous, long-term modeling of low and high flow diminishes or exacerbates the problem; and (4) clarify how input-driven discrepancies in floodplain inundation predictions propagate from upstream to downstream, from small upstream catchments to large lowland catchments.

The results of the numerical experiment highlighted the high sensitivity of floodplain inundation predictions to predicted streamflow peak values. Moreover, complex morphological features and low-accuracy topographic data hampered accurate flood modelling at the basin scale and the proposed methodology was able to pinpoint areas requiring further data collection. Finally, when modelling a long time series of low- and high-flow periods, uncertainties in the inundation patterns increased over time and when moving from upstream to downstream areas of the basin along the river path. Consequently, it is suggested that more accurate peak discharge predictions, better knowledge about critical morphologic terrain features, event-based modelling, and data assimilation of inundation extents and water levels in both low- and high-flow periods may provide a pragmatic strategy to achieve acceptable skill in time-continuous flood inundation modelling. The methodology presented in this study is relatively simple and based on the modelling of two time series only to limit computational cost; nevertheless, it has the potential to enable the identification of areas requiring tailored modelling solutions and data collection.

Keywords: *Floods, coupled hydrologic-hydraulic modelling, error propagation, large scale*

Improving parameter estimation in ecohydrologic multi-objective calibration and validation

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Abstract: Hydrologic models have proliferated in hydrology, being used by academics, government agencies and business alike. Models aim to capture the complexities of nature more simply, which can result in uncertainty and equifinality, where several parameter sets can deliver similar model performance.

Part of recent model development has focused on minimizing uncertainty, with multi-objective calibration suggested as a possible solution. One approach to multi-objective calibration uses two data sets in calibration, for example, streamflow and leaf area index, to better constrain model parameters. Although calibrating on multiple data sets can improve model outcomes, the addition of supplementary data does not guarantee improvement. Adding extra data sets can increase the number of non-unique parameters sets giving equivalent optimal simulation solutions as a result of trade-offs. These trade-offs can be visualized by plotting objective function values on a Pareto front. Developing a Pareto front does not highlight a unique 'best compromise' parameter set and searching the front for this can be time-consuming. Furthermore, there have been few comparisons of Pareto front solutions between calibration and validation using independent data.

One solution may be provided by exploring parameters trade-offs in calibration and validation via uncertainty analysis. Bayesian frameworks have been well established to evaluate parameter uncertainty related to model calibration and can also be used in a multi-objective setting. Bayesian approaches define distributions of model parameters to characterize model uncertainty. However, this does not reduce the number of equivalent parameter sets identified during calibration.

To extend earlier research, this study implements a Bayesian approach to multi-objective calibration of an ecohydrologic model aiming to evaluate and target Pareto front difference in calibration and validation. The model implemented is an earlier used combination of HYMOD and a modified Bucket Grassland Model (BGM). Using the Corin Catchment in the Australian Capital Territory, Australia, as a focus area, gauged streamflow (Q), MODIS leaf area index (LAI) and actual evapotranspiration (ET) between 2008 and 2018 was used for calibration and validation. The Bayesian analysis meant that the relative information content for streamflow predictions between leaf area index and evapotranspiration data could be identified.

Results indicate distinct differences in the Pareto fronts between the LAI and ET data combined with the Q data. This occurred despite the strong coupling of LAI and ET in the model, and the same ecological parameters driving both ET and LAI, highlighting the difference in information content between the two datasets. The validation Pareto fronts deviated from those generated during calibration. This suggests that parameter sets identified as being on the front during calibration perform differently during validation. Most sets underperform during validation; however, several sets outperform their calibration results during validation. It is as of yet unclear what has driven this improvement.

Moving forward, Bayesian analysis will also be run on these points, with the intention of investigating if the uncertainty identified by this method differs between points on the previously established Pareto front.

Keywords: *Calibration, validation, Pareto front, Bayesian inference, ecohydrology*

Do state error models improve hydrologic predictions?

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Abstract: Accurate model parameter estimates are requisite for water resources planning and management studies. In order to simulate various water resource scenarios, an appropriately parameterised baseline model must be established that represents the existing system. Baseline rainfall-runoff model parameters are usually obtained via calibration using observed streamflow. Since uncertainties exist in the observational data and the model structure, parameter distributions can be obtained (rather than a single optimal set) using Bayesian uncertainty analysis. However, reliable inferences require that appropriate error models are used in the likelihood formulations, the construction of which are often complicated and subjective. For example, a residual error model is typically used that represents the aggregation of all data and structural errors. This approach is ostensibly simple, however one has to commit to a characterisation of the lumped error which is often difficult given the multiple sources of error in hydrologic systems. If certain errors are neglected or mis-characterised, there is a real risk that parameter estimates, and therefore predictions, will be biased.

Errors which are commonly ignored during batch calibrations are the hydrologic state errors. Hydrologic models typically compute values for multiple states during each time step. These are used as input for subsequent time steps since direct state observations do not exist in many applications. However, model structural deficiencies or input data errors may cause mis-approximation of the states on any given time step. These are particularly problematic since these errors can propagate over multiple time steps.

A synthetic study examines the effect of state errors on parameter estimations for a daily rainfall-runoff model (GR4J). The soil moisture state was corrupted with 87 intermittent errors spread over a 10 year period. Then parameters were re-estimated using a classical aggregated residual error approach in the likelihood function. This was shown to give biased parameter distributions shown by the blue distributions in Figure 1. But the use of a limited state error model, with only 20 state corrections throughout the time series, was able to predict the parameters more accurately (green distributions in Figure 1). In addition, parameter uncertainty analyses were performed on real data for a catchment in southeast Australia (Jingellic Creek at Jingellic), to see whether the use of a simple state error model would provide better streamflow predictions in a 10 year evaluation period than without. Results showed that using the state error model predicted streamflow better than the classical approach, e.g. stochastic runs using the state error model only failed to predict observed flow for 7% of evaluation days, opposed to 11% for the classical approach (Figure 2).

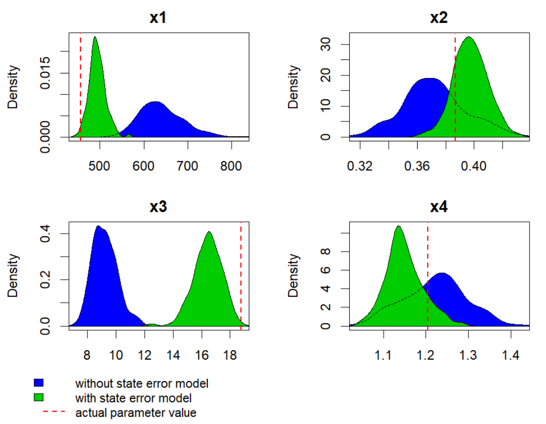

Figure 1. Synthetic study's distributions of the rainfall-runoff model (GR4J) parameters obtained from the uncertainty analyses.

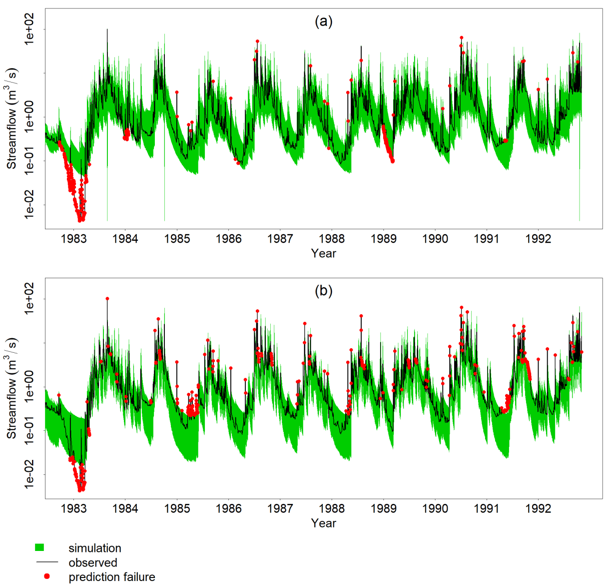

Figure 2. Evaluation period time series plots of stochastic runs (a) using a state error model; and (b) without using a state error model (classical approach).

Keywords: *Bayesian uncertainty analysis, parameter uncertainty, MCMC, state uncertainty, water resources*

A global sensitivity analysis for spatially distributed watershed models: a holistic analysis applied to SWAT for input datasets and model parameters

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Abstract: Deterministic environmental models offer useful methods for exploring environmental resource problems, providing predictions, and supporting decisions that involve complex environmental phenomena evolving in space and time. It has become increasingly recognized, however, that these models must address uncertainties, especially those related to possible management actions. Sensitivity analysis (SA) evaluates the change in model output(s) with respect to changes in model factors (usually parameters, forcing and other input data). It can be a useful first step in addressing the criticality of uncertainty sources by assessing those factors, and their plausible range of values, that dominate changes in model outputs. However, SA for environmental models remains incomplete in terms of addressing all sources of uncertainty; model structure input parameters and datasets.

The purpose of this project is to illustrate how a more holistic SA approach to spatially distributed environmental models, can be used to identify their critical sources of uncertainty. First, this project addresses the uncertainty of model structure input parameters related to the submodels of the SWAT application. It also explores the measurement uncertainty of the DEM and the uncertainty of boundaries of classes in Land Use Land Cover (LULC) and soil datasets. Second, the impact of measurement errors in meteorological information is investigated. Finally, the SA is also applied to the model parameters investigated as has been the primary focus. This study is conducted with an application of the Soil and Water Assessment Tool (SWAT) in the Minjiang River watershed in Sichuan using the extended Fourier Amplitude Sensitivity Test (FAST).

This project follows a general process of SA: identifying uncertainty sources associated in SWAT, propagating the uncertainty from the identified source, and implementing SA. This project identifies uncertainty sources related to model structure input parameters and datasets, as well as general model parameters. Then, uncertainty propagation methods are utilized to their corresponding uncertainty sources. For spatial input datasets, the measurement uncertainty of DEM is propagated using a sequential Gaussian simulation to represent spatially autocorrelated uncertainty, and the boundary uncertainties of LULC and soil datasets are simulated by adopting the epsilon band. The uncertainty propagations for model input parameters [e.g., a threshold for stream network designation, the initial curve number of moisture condition (CN2), the threshold depth of water in a shallow aquifer (GWQMN), and nitrate percolation coefficient (NPERCO)] are modelled based on a uniform distribution with their realistic ranges. SA evaluates the relative importance of the uncertainty sources in the average streamflow (FLOW) and loads of nitrate (NO3) and total phosphorus (TP).

The analysis reveals that the precision of a stream network in the watershed delineation is the most critical uncertainty source of variations in FLOW, NO3, and TP. The precision of a stream network shows a significant negative relationship with the number of generated subwatersheds, which indicates that the number of subwatersheds and the watershed delineation model can substantially affect SWAT estimations. The SWAT parameters, i.e., CN2, GWQMN, and NPERCO, are other important uncertainty sources. Finally, measurement uncertainty of precipitation would not be negligible on FLOW and NO3 variations.

Keywords: *Uncertainty, model structure uncertainty, sensitivity analysis, SWAT, watershed delineation*

Applying rainfall ensembles to explore hydrological uncertainty

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Abstract: The widespread presence of spatial and temporal variability in rainfall is well known. However, this variability can not be captured by point gauge measurements alone. An accurate representation of this variability is crucial for hydrological and meteorological applications. Precipitation information is an essential input for all hydrological models, but can be especially challenging in regions where no or very few rain gauge stations are established. Moreover, the uncertainties involved in these rainfall inputs are usually not considered or ignored in the hydrological simulations. Uncertainty in precipitation input arising from errors in spatial representation, measurement or estimation accuracy, can create uncertainty in the streamflow estimation. In such cases, the use of high resolution rainfall ensembles can play crucial role in modelling the rainfall-runoff relationships, particularly for high flows or flash floods. This study aims to characterise the hydrological uncertainty involved in the high flow simulations using rainfall-runoff models.

This study focuses on characterising uncertainty in rainfall-runoff model outputs through the application of ensemble precipitation estimates. We demonstrate the results for selected events in the Macleay River Basin using a simple rainfall-runoff model. The basin is situated in the New South Wales (NSW), mid-north coast of Australia and is prone to flash floods. Historically, flooding in the lower Macleay Valley occurs at every 2 or 3 years, and the largest floods have occurrence interval of 100 years. We also explored the response of basin area on this uncertainty and the cascading of this uncertainty from upstream to downstream of the basin.

The GR4H model, which is an hourly implementation of GR4J, is merged with Muskingum Routing in this study. We used GPM (Global Precipitation Mission) precipitation data at 10km x 10km spatial resolution further downscaled to 2km x 2km spatial resolution for three years (2015-2017). Further, radar data along with the GPM precipitation is used to create 50 member ensemble rainfall estimates at 2km x 2km spatial and hourly temporal resolution. In order to analyse the impact of rainfall uncertainty on streamflow we selected some of the high flows events. The three sub-basins having an area between 377-860 km^2 along with the Macleay Basin (~8,000 km^2) is used to run the simulations. Further, we compared and contrasted the runoff generated at the outlet by grid-wise simulations, basin averaged simulation, and simulations from ensemble rainfall as input with the observed streamflow.

The results show that the grid-wise streamflow generation are comparatively better in capturing the peak flow events in the Macleay Basin and sub-basins than the basin-wise streamflow output probably due to the use of the same parameter throughout the simulations, lower averaged streamflow at each sub-basins, and more amount of overall losses at the basin scale. The observed peak flow is within the range of streamflow simulated using ensemble rainfall for all the basins.

The application of interest to this study is the use of ensemble precipitation forecasts to generate ensemble streamflow forecasts. This study shows that the rainfall-runoff modelling with ensemble precipitation inputs can considerably reduce the amount of uncertainty in simulation results, particularly in data-sparce regions.

Keywords: *Precipitation, hydrological uncertainty, rainfall ensembles, streamflow*

Rainfall-Runoff Analysis by Bayesian Inverse Methods

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Abstract: Over the past century, hydrologists have developed sophisticated methods for the correlation and prediction of streamflow from rainfall data, including protocols for hyetograph and hydrograph separation, and deconvolu-tion to determine the unit hydrograph. Very recently, some researchers have advocated an alternative approach in which the hydrological system is treated as a simple dynamical system, for example [1; 2; 3]:

$$y_t = \alpha + \beta u_t + \epsilon_t \tag{1}$$

where y_t is the streamflow (possibly in transformed form), u_t is the rainfall (or other climate proxies), ϵ_t is the error or stochastic component, α and β are parameters and t is a time index. The parameters are then calculated by linear regression [2; 3]. Recently, this approach was used to interpolate a 1 km resolution daily streamflow and hydrological metrics dataset for all of Germany [3]. Eq. (1) has been subject to the obvious criticism that it does not include other variables, in particular the catchment characteristics [2]. In addition, reported studies have required *ad hoc* data processing, for example to eliminate inferred negative streamflows [3]. To address these criticisms, more complicated models have been proposed, for example [2]:

$$\mathbf{x_{t+1}} = \mathbf{A}\mathbf{x_t} + \mathbf{B}\mathbf{u_t} + \boldsymbol{\epsilon_t}, \qquad \mathbf{y_t} = \mathbf{C}\mathbf{x_t} + \mathbf{D}\mathbf{u_t} + \boldsymbol{\eta_t} \tag{2}$$

where $\mathbf{x_t}$ is the system vector, $\mathbf{y_t}$ is the streamflow vector, $\mathbf{u_t}$ is the rainfall or climate variable vector, $\boldsymbol{\epsilon}_t$ and $\boldsymbol{\eta}_t$ are noise vectors, and $\mathbf{A}$ to $\mathbf{D}$ are parameter matrices. Eqs. (2) can be extended further to include derivatives, multiple time steps, nonlinear functions or mechanistic insights [e.g., 1, 4]. While such models are empirical, they are no more empirical in practice than many physical hydrological models based on assumed or lumped parameter values, and also make no *a priori* assumptions on the baseflow or infiltration characteristics, or uniqueness of the unit hydrograph.

In this study, we consider the problem of parameter identification for linear or nonlinear hydrological dynamical system models (1)-(2), in general based on a regularisation or sparse regression method. We demonstrate that such methods fall within the framework of Bayesian inverse methods. In their simplest form, the Bayesian maximum *a posteriori* method can be shown to be equivalent to Tikhonov regularisation based on Euclidean norms [e.g., 5]. This viewpoint provides a Bayesian rationale for the choice of residual and regularisation terms, respectively from the Bayesian likelihood and prior. For hydrological variables such as rainfall and runoff – which cannot be negative – this also provides a rigorous approach to implement alternative distributions, such as lognormal distributions. At the next level, the Bayesian framework enables the estimation of uncertainties in the inferred parameters and the model, the ranking of models by posterior Bayes factors, and the estimation or elimination of intermediate variables. At the highest level, Bayesian algorithms such as Markov chain Monte Carlo methods or nested sampling can be used to explore the posterior probability distribution, should this be desired. We demonstrate these features of Bayesian rainfall-runoff analysis using data from several sources, including Australia and Germany.

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Keywords: *Rainfall-runoff analysis, hydrological dynamical systems, Bayesian inference*

Global uncertainty analysis in irrigation scheduling

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Abstract: Agriculture is the greatest consumer of water resources globally, with an average of 70% of freshwater consumed for irrigation. Irrigation water use is often inefficient; therefore, significant water savings and sustainability improvements can be achieved by increasing irrigation efficiency. Efficient irrigation requires a good understanding of how much and when to irrigate. However, such understanding is often limited by uncertainties associated with available information on soil, crop, climate and field management. This study aims to quantify input uncertainties in irrigation scheduling. This is achieved by implementing global sensitivity analysis on a simple and robust irrigation simulation model with uncertain inputs. Model inputs include weather data, soil properties, crop characteristics and management factors.

The model represents the soil water balance of an irrigated field using a bucket that is filled by irrigation and rainfall, and depleted by evapotranspiration and deep drainage. The size of bucket is defined from Field Capacity (*FC*), Wilting Point (*WP*) and root depth. Time to irrigate is determined by the water content falling below a storage threshold, which depends on crop type and management strategies. Actual evapotranspiration is calculated from the Penman-Monteith method represented by the Food and Agriculture Organisation (FAO) by multiplying a weather-based reference evapotranspiration with a crop coefficient (K_c) that is defined by specific crop type. The model includes the effect of crop water stress once the soil water content drops below a certain threshold determined by the crop type, which decreases actual evapotranspiration. The sensitivity of time-to-irrigate to input uncertainties is calculated within one irrigation interval commencing with a full bucket (*FC*) as the initial condition.

The Sobol' sensitivity analysis method is used, where the idea is to decompose the variance of the model output into contributions from individual inputs and their interactions. The actual range of uncertainty in a number of inputs is used, including: dew-point temperature, minimum and maximum temperature, wind speed, solar radiation, rainfall, *FC*, *WP*, root depth, K_c and depletion factor. The uncertainty in weather data is considered in forms of bias and noise error, while the error for other parameters is included within a reasonable range.

Results show that irrigation is mostly sensitive to uncertainty in *FC*, root depth, *WP*, K_c and wind speed; however, the order of importance varies depending on soil type, crop type, climate and management. *FC, WP* and root depth represent the extractable soil water content (bucket size), while wind speed, the highest influencer on reference evapotranspiration, alongside K_c represent actual evapotranspiration which is an important element of the soil water depletion rate. For coarser soils where the bucket size is typically smaller, wind speed and K_c have the most impact on model results, implying that the depletion rate is the most important source of sensitivity, especially where the irrigation strategy aims to avoid water stress. As the bucket size increases, that is for finer soils, *FC* and *WP* become the largest sources of sensitivity. Overall, the results present a comprehensive understanding of model sensitivity in irrigation scheduling applications.

Keywords: *Decision making, global sensitivity analysis, irrigation scheduling, uncertainty analysis*

Error estimation of satellite signal-based river discharge using double instrumental variables method

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Abstract: River discharge is an important hydrologic variable for flood forecasting and water resources management. However many regions suffer from a lack of ground-based river discharge observations because of delays in data release, sparse distributions of river gauges or expensive maintenance and operation costs. Satellite data which have near-real time access, global coverage, and low cost can provide useful information to observe dynamics of surface water in ungauged regions. Recently, tremendous efforts have been devoted to detect, monitor, and estimate river discharge from satellite signals derived from the Global Flood Detection System (GFDS). The satellite signal is a ratio of satellite-observed passive microwave brightness temperature of a wet area to that of a dry area, and is closely related to surface water dynamics because of contrasted thermal emissivity over the wet and dry areas. Previous studies have widely used such satellite signals for detecting floods, estimating river discharge and calibrating hydrologic models. Although satellite signals can be potentially used for improving these types of hydrologic applications, fewer efforts have been made in quantifying uncertainties in the satellite signal data. The errors in satellite signal data are caused by errors in sensors, land surface conditions (water extents or river morphology) and atmospheric conditions (clouds or temperature). These errors can be propagated into river discharge estimations and hence provide less accurate calibrated parameters, flood detection, or forecasts. Therefore error estimation of satellite signals is necessary to provide reliability of the hydrologic applications.

Due to a lack of suitable ground observations, large spatial scale validation of remotely sensed data is often difficult. For this reason, a cross-comparison approach such as triple collocation (TC) has been used to estimate errors of large-scale data. The TC method compares three independent products to estimate the error variances in all products and the individual product-truth correlations. However, the TC method requires three independent products that are often not available in practice, especially for satellite signal data. This study adopts a double instrumental variables (IVd) method which uses only two independent products to estimate error variances and product-truth correlations. Here we used two flood magnitude data (*FM*) derived from two satellite signals GPM and AMSR-2 as two independent products. We used daily *in-situ* river discharge (*Q*) at 206 Hydrologic Reference Stations (HRSs) over Australia from 01/2015 to 04/2019 as a reference data. The HRS river discharge was standardised to be consistent with the two *FM* products. In addition, 1-day lagged time series of the *FM* (*FM-lag*) was used as a double instrumental variable for the IVd analysis. The *FM* data-truth correlations estimated by the IVd method were compared to the linear correlations between the *FM* and the standardised river discharge. We then present the strength of the pixel-wise data-truth correlations in different conditions across Australia to establish the conditions under which satellite signals may be useful for hydrological applications.

Keywords: *Satellite signal, river discharge, error estimation, double instrumental variables, Australia*

Probabilistic indicators for soil and groundwater contamination risk assessment

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Abstract: Models are essential tools for the management of scarce soil and water resources. In recent years various approaches have emerged to model the feedback between biomass dynamics, water flow, solute transport and kinetic biodegradation processes in agricultural soil, all addressing the risk of contamination and pollution of soil and water resources. While model parameters remain hard to determine, the impact of uncertainty on our ability to monitor and control agricultural soil contamination has been poorly explored in the literature.

In this work we present a new global sensitivity index (*AMAP*) to rank the contribution of uncertain parameters for the probability of a target quantity to exceed user-defined safety limits. The definition of this new index is grounded on recently proposed moment-based global sensitivity indices. We tested the application of *AMAP* to soil and aquifer contamination and pollution by the herbicide glyphosate (GLP) and its toxic metabolite aminomethylphosphonic acid (AMPA) in a wheat field, upon leveraging on previous work from our group. We study the impact of soil hydraulic parameters on soil and water contamination probability through a global sensitivity analysis (GSA). Target quantities are GLP and AMPA aqueous concentrations in the soil column as well as their leaching below the root zone. The GSA was repeated to encompass six scenarios of managed water amendments and rainfall events including time-resolved and stationary ecohydrological boundary conditions. *AMAP* shows that, among the tested uncertain parameters, absolute permeability, air-entry suction, and porosity have the greatest impact on GLP and AMPA probability to pollute the aquifer (i.e., exceedance of aqueous concentration thresholds). In scenarios of dry and wet conditions, maximum *AMAP* values diverged only slightly as compared to aquifer pollution in the reference scenario. However, parameter-specific *AMAP* values showed important variations across scenarios, thus leading to different parameters rankings. The proposed index *AMAP* can be effective to thoroughly explore time histories arising from model-based predictions of environmental pollution hazards and therefore support informed decision-making in risk assessments. The analysis is then expanded to analyze risk assessment in geographically distributed predictions of soil contamination. In such a numerical analysis we consider datasets mapping global distributions of soil hydraulic properties, as well as dynamic hydrologic boundary conditions and temperature fluctuations. The results may be next used to direct future environmental monitoring operations and detailed characterization in contamination hotspots.

Keywords: *Sensitivity analysis, reactive transport, glyphosate, uncertainty quantification*

Assessment of uncertainty in modelling annual impacts of farm dams for Victoria

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Abstract: Information about farm dams is required for Victorian water resource planning processes, including the Long Term Water Resource Assessment, and Sustainable Water Strategies. In addition, farm dam information is an essential part of the Murray Darling Basin Plan Water Resource Plans and the Victorian Water Accounts. As part of an ongoing program to improve understanding of farm dam impacts, an annual dam accounting model (ADAM) was developed which can estimate impacts of farm dams across Victoria at an annual time step. While ADAM has been successfully applied, it was recognised that many of the model inputs contain significant uncertainty.

To better understand this uncertainty, ADAM was adapted to incorporate Monte Carlo sampling of uncertainty in nine aspects of model input and structure. The method of sampling from the nine uncertainty distributions varied from variable to variable, with some elements sampled one per farm dam and others involving more complex spatial correlation and temporal variation. The effect of each uncertainty element was considered both independently and in conjunction with the other elements. The model was run for 100 replicates, and the total uncertainty in impact on total surface water runoff was quantified at both a state and basin level.

On a state-wide basis, the median estimate of the mean annual impact with consideration of all uncertainties was about half of the base case estimate from ADAM, as shown in Figure 1.

By far the most influential model input in the overall uncertainty was the runoff per unit area estimated from AWRA-L. The next most influential were temporal variation in dam surface area, evaporation, upstream catchment area and demand factor. Because of the threshold nature of the impact calculation in ADAM (that is, impact is capped at farm dam inflows) the sensitivity to different parameters is non-linear; when inflow is constraining, the sensitivity to net evaporation plus demand is low. It was found that even in the base case scenario inflow was constraining for the vast majority of farm dams, and this was exacerbated when uncertainty was considered.

In addition to the sensitivity of farm dam impact to uncertainty in model input and structure ADAM was also highly sensitive to the assumed degree of spatial correlation of uncertainty. For this study a coarse assumption of spatial correlation was made; farm dams within each sustainable diversion limit (SDL) tributary had correlated uncertainties. This assumption of spatial correlation should be further examined in future work.

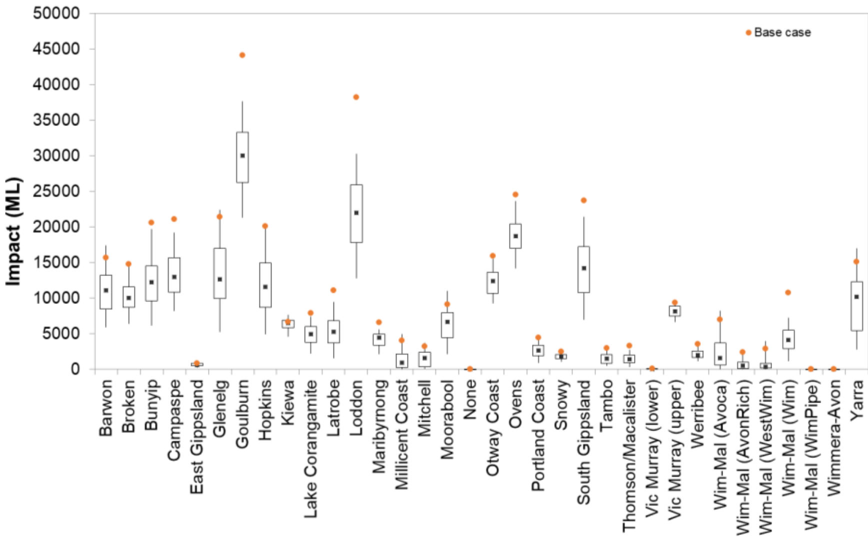

Figure 1. Total uncertainty in farm dam impact for each basin over the year 2016

Keywords: *Water accounting, Australian Water Resources Assessment-Landscape (AWRA-L)*

Validating satellite precipitation products through input to a commonly-used hydrologic model

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Abstract: In large catchments, the spatial distribution of rain-gauge networks is important for capturing average rainfall depths for use in hydrologic models. Where gauge density is inadequate, point measurements may misrepresent the overall rainfall amount potentially leading to poor model performance. As an alternative to gauge data, numerous satellite precipitation products (SPPs) are available for hydrologists modelling large catchments. These products are either uncorrected products using only satellite data or corrected products based on gauge and/or (re)analysis data. It is common practice to validate satellite precipitation through comparison with rain gauge data. However, in many cases the rainfall statistics that are important for accurately simulating streamflow are not intuitive. For this reason, rather than comparing rainfall statistics directly, we assess satellite rainfall as a hydrologic model input. This involves calibrating a hydrologic model with various products to see which is able to give the best streamflow simulation.

The uncorrected SPPs in this study are the TRMM Multi-satellite Precipitation Analysis Real Time (TMPA-3B42RT) and the Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN). Two corrected SPPs based on satellite and gauge data (TMPA-3B42 and PERSIANN-CDR) and the Multi-Source Weighted-Ensemble Precipitation (MSWEP) are also included. These products combine satellite, gauge and reanalysis data.

The study catchment is Reedy Creek in Victoria (Hydrologic Reference Station 403209A), which has an area of 5500 km^2 and contains 23 gauges covering the study period 01/06/2003 to 31/05/2013. Thiessen polygons were delineated to derive area-weighted gauged rainfall over the catchment. This was used as an input to the conceptual hydrologic model GR4J. Daily satellite precipitation from the five aforementioned SPPs was weighted based on grid cell area inside the catchment and also applied in the GR4J model. Potential evapotranspiration was the same for all simulations, estimated based on the McGuiness-Bordne formula. Figure 1 shows the results of calibration over the ten-year period against streamflow data in terms of Nash-Sutcliffe Efficiency (NSE).

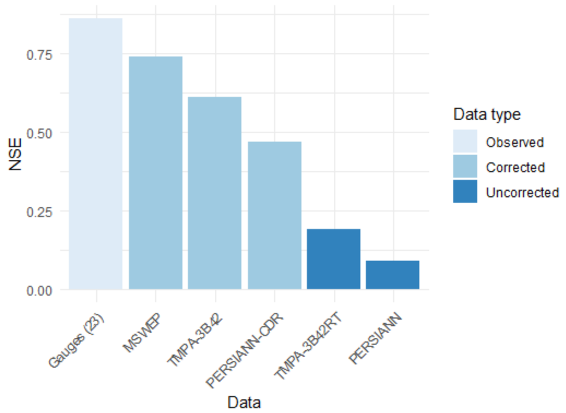

Figure 1. Model calibration results

These results give an indication of how well GR4J is able to simulate streamflow with each input rainfall series. High calibration NSE indicates the dataset represents the rainfall statistics such that the model is able to reproduce the observed streamflow series well. The rain gauge data clearly outperformed all of the SPPs when 23 gauges were available. The uncorrected SPPs performed worse than the corrected SPPs. Among the three corrected SPPs, the model using MSWEP data had the best performance. The TMPA-3B42RT based on passive microwave data slightly outperformed the PERSIANN using infrared-based dataset.

It is also important for hydrologists to understand the gauge density required for point measurements to outperform gridded satellite products. This aids in selection of the best available dataset for each application. As a next step, we repeatedly removed a given number of gauges at random and recalculated the rainfall series with reduced gauge density. For the Reedy Creek catchment, we found that gauge data generally outperformed even the most reliable SPP until the number of gauges was reduced to two. This will be investigated further in later work.

Keywords: *Satellite precipitation, rainfall gauge, data uncertainty, catchment modelling*

Evaluating the impact of the vegetation dynamics on streamflow predictions using Bayesian Ecohydrologic modelling across catchments in Australia

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Abstract: Vegetation processes play a significant role in the watershed hydrologic cycle. Ecohydrologic modelling that combines hydrologic and vegetation models to simulate the interrelationship between the water cycle and vegetation dynamics has thus become a central topic in recent years. Ecohydrologic models are generally more complex than hydrologic models, and usually require multiple datasets as inputs in the model. As a result, ecohydrologic models may be more susceptible to model uncertainty. It is therefore important to include appropriate model uncertainty analysis associated with model calibrations. Bayesian inference, which combines available prior information on the model and the data, has emerged as a powerful tool for quantifying model uncertainties. Previous work has demonstrated the importance of multi-objective calibration approach for simultaneously calibrate both hydrologic and vegetation variables in ecohydrologic modelling. In this work, we aim to further investigate the impact of the vegetation dynamics on the streamflow simulation.

We applied the Bayesian multi-objective approach to calibrate both streamflow and Leaf Area Index (LAI) using a conceptual ecohydrologic model that combines a hydrologic model (HYMOD) and a Bucket Grassland Model (BGM). We selected 14 catchments with different hydrologic characteristics and types of land cover across Australia. Results are compared with the single objective calibrations on streamflow/leaf area index. Model performance (Mean Square Error) for the low/median/high flow is evaluated. Results show that the impact of the vegetation on the streamflow prediction is different for different catchments. The streamflow predictions can be significantly impacted by the LAI for arid catchments. There is no significant impact for wet catchments, but the posterior distributions for hydrologic parameters can be different comparing the multi-objective case and the streamflow only case studies.

Keywords: *Ecohydrologic modelling, Bayesian inference, multi-objective calibration, uncertainty analysis*

Role of Wiener chaos expansion in modelling randomness for groundwater contamination flow

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Abstract: Pertinent mathematical modelling plays pivot role in making groundwater protection and reclamation policies. Uncertain parameters and several basic phenomena in almost all branches of engineering and science can be modelled efficiently with the help of Stochastic Partial Differential Equations (SPDEs) and their behaviour can be interpreted more accurately. The intent of the present study is to use an efficient numerical approach based on Wiener chaos expansion to understand the stochastic nature of variables associated with groundwater flow. First and second order moments of concentration profile are calculated and plotted graphically. Obtained results are in good aggrement with those available in existing literature.

Keywords: *Stochastic partial differential equations, Wiener chaos, hermite polynomials, stochastic simulation, brownian motion*

A new Bayesian calibration algorithm to quantify input uncertainty for hydrological models

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Abstract: Parameter estimation in hydrologic models is affected by uncertainties in the measured input/output data (typically, rainfall and runoff, respectively), as well as model error. Despite advances in data collection and model structure specification, we expect input uncertainty to be particularly significant (because of the high spatial and temporal variability of precipitation) and to remain considerable in the foreseeable future. Ignoring input uncertainty potentially yields biased and misleading results. Precise and reliable predictions thus need proper quantification of input errors in hydrologic model inference.

Despite this importance, the current approaches to characterization of input error cannot approach the exact values of time-varying errors, and instead attempt to specify the time-varying error uncertainty. Two problems arise in this process. The first is how to efficiently estimate the input error given the total model error (in which multiple error types are propagated and combined). Secondly (and related), how to address issues of error autocorrelation, such that input errors persist in model outputs over multiple time steps. Addressing these problems is non-trivial and has yet been considered sufficiently.

This study investigates a new algorithm in the context of Bayesian statistical inference to address the above problems. The approach has three main novelties. First, the approach makes use of the prior knowledge of the input error distribution to improve the identifiability of the error values through optimising the order of input errors rather than optimising their actual value. Second, the approach applies Newton's method to identify the input error, proving to be far more efficient than other approaches. Finally, the approach works to reconstruct the expected catchment output from its corresponding input and subsequently identifying the memory of the hydrologic system. Based on results from synthetic data and real data, the new algorithm can efficiently and effectively quantify the input errors of each time step, and improve the model parameter estimation by eliminating the noise caused by imprecise inputs. What's more, it is flexible, and can easily be extended to water quality models and other water resource predictions.

Keywords: *Bayesian inference, input uncertainty, uncertainty quantification, Newton's method, autocorrelation*

Modelling the responses of marine ecosystems to climate change impacts

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Abstract: Marine ecosystems comprise diverse plants and animals. They provide food for millions of people, regulate the climate, protect coastal areas from storms, support various livelihoods and recreational activities. Unfortunately, marine ecosystems are at risk due to climate change impacts and human activities. Climate change has tremendous impacts on marine ecosystems and on the economic and social services they provide. To predict the effects of climate change on marine ecosystems and the effectiveness of intervention strategies, we need reliable marine ecosystems response models that reproduce climate change effects and frame predictions in ways that make them suitable for policy decisions. Complex biogeochemical models are used to predict marine ecosystems' responses to impacts of climate change. Research to predict climate change responses of marine ecosystems has led to the development of many biogeochemical models with varying process representations and complexities. We conducted a systematic review on the representation of climate change in marine biogeochemical models with the Web of Science search results in order to identify well-implemented aspects and knowledge gaps of marine ecosystems response modelling.

In this review, peer reviewed journal publications and proceeding papers were selected for inclusion based on their use of mechanistic models to project the effects of climate change on marine ecosystems and their relevance to modelling marine ecosystems' responses to impacts of climate change. We identified well-implemented aspects of marine ecosystem modelling: these include scenario analysis using long continuous runs, assessment of model performance against quality-controlled observational data, and coupling of biogeochemical models with physical-ocean-atmosphere models. As an example, Table 1 is a summary of one of the approaches used to consider the effects of changes in river discharge.

Consideration	Approach	Advantages / Disadvantages	Number of studies using this approach
Changes in river discharge	Application of a hydrological model under climate change scenarios to obtain input river discharge.	Requires detailed information on physical processes, thus provides an understanding of hydrological processes affecting river discharge behaviour. Captures the impacts of climate variability. Most accurate in simulating river discharge changes. Large computational cost. Existence of complexity and uncertainties associated with climate model runs.	10

Table 1. Summary of an approach used to consider the impacts of changes in river discharge.

However, important aspects of marine ecosystem modelling have often been neglected: these include the use of multiple IPCC scenarios to assess the range of possible outcomes, ensemble modelling to evaluate uncertainty, use of independent validation datasets, the consideration of the effects of changes in cloud cover, evaporation, wind speed, sea level, storm frequency and storm intensity, and the incorporation of species adaptation to changing environmental conditions such as changes in temperature response functions and ocean acidification. The outcome of this study could help improve the reliability and accuracy of marine ecosystems response models.

Keywords: *Climate change, marine ecosystems, biogeochemical models*

Future freshwater inflows to the Baltic Sea under changing climate and socioeconomics: upscaling local effects

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Abstract: The Baltic Sea is suffering from eutrophication caused by nutrient discharges from land to sea. These freshwater inflows vary in magnitude from year to year as well as within each year due to e.g. natural variability, weather patterns, and seasonal human activities. Changing climate and socio-economics contribute additional uncertainty to estimation of the freshwater inflows to the Baltic Sea that needs to be taken into account when planning management practices and mitigation measures.

Continental to global scale hydrological models have emerged in recent years as tools e.g. for flood forecasting, large-scale climate impact analyses, and estimation of time-dynamic water fluxes into sea basins. E-HYPE is a pan-European application of the HYPE model developed as a multi-purpose tool for large-scale hydrological and environmental analyses. HYPE (https://hypeweb.smhi.se/) is a process-based, semi-distributed rainfall-runoff model capable of simulating several water quality constituents.

We compared current freshwater inflows from land with those from dynamic modelling with E-HYPE using projections of climate change (RCP8.5) and scenarios of shared socioeconomic pathways (SSPs) for 2050s. We selected a range of climate models and socioeconomic assumptions to evaluate possible effects and to estimate the uncertainty and then evaluated impacts of selected nutrient mitigation measures under this range of conditions. While climate change affects nutrient loads to the Baltic Sea, these impacts can be overshadowed by the impacts of changing socioeconomic factors such as land use, agricultural practices, population changes, dietary changes, atmospheric deposition, and waste-water collection and treatment by mid-century (Bartosova et al, accepted to Ambio 2019).

The projected impacts of changing climate and socioeconomics can be contrasted with efficiencies of more traditional nutrient mitigation measures such as buffer strips, wetlands, stormwater ponds, as well as more innovative measures such as spatially differentiated strategies focused on nitrate reduction in groundwater. The impact of measures was first simulated within pilot areas. The effects were then upscaled and interpreted within E-HYPE in order to calculate potential impact on the nutrient loads to the Baltic Sea. The upscaling process utilizes local knowledge and transfers the process understanding from high resolution models to the coarser, pan-European scale E-HYPE model.

The impacts from the traditional measures ranged from 0% to 2% reduction in nitrogen or phosphorus load. The nitrogen loads to the Baltic Sea were reduced by about 5% when the measures targeting reduction of N in groundwater were considered. The nitrogen loads were reduced by 17% in Western Baltic Basin where conditions are more favorable for the measure implementation, i.e. more intensive agriculture over soils with a larger nitrogen reduction potential.

Our findings indicate that average nutrient loads are expected to increase by 8% and 14% for nitrogen and phosphorus, respectively, as a response to climate change on average. However, changes in the socioeconomic drivers can lead to significant changes in the loads, ranging from a decrease by 13% and 6% to an increase by 11% and 9% in nitrogen and phosphorus loads, respectively, depending on the socioeconomic pathway to be followed.

Local measures have a diminishing effect on nutrient load reductions when comparing impacts on local rivers with impacts on loads from larger river basins to the Baltic Sea. These results suggest a possible contradiction between the load reduction goals for the Baltic Sea and the locally prioritized goals.

Keywords: *Baltic Sea, nutrient loads, E-HYPE, nutrient mitigation measures, upscaling*

Simulation of the suppressive effect of zinc on cyanobacteria in paper mill wastewater

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Abstract: Harmful algal blooms (i.e. blue-green algae or cyanobacteria) and their impacts are a recurring and significant issue worldwide. Factors supporting the extensive growth of cyanobacteria include warmer temperatures, sufficient levels of reactive nitrogen and phosphorus, reduced rainfall, long hydraulic retention times within the water body (slow-moving water) and adequate sunlight. Problems associated with the growth of cyanobacteria include formation of unpleasant odours and toxins that have the potential to harm humans and wildlife that come into contact with contaminated water.

Aerated stabilization basin (ASB) systems, commonly used by the pulp and paper mill industry for treatment of wastewater, are predominantly light limited due to high colour and consequently, blooms of cyanobacteria have been reported to rarely occur in pulp and paper ASBs. However, with the relatively low colour of paper mill (PML) wastewater (without integrated pulping processes) in ASB treatment with long hydraulic retention times (HRTs), there would be risk of occurrence of cyanobacteria at bloom levels. In 2014, two occurrences of cyanobacterial blooms were observed at a PML site in South Australia and in April 2016, *Microcystis aeruginosa* occurred at bloom levels (> 10^6 cells/mL) in an ASB pilot plant (3 tanks of ~200 L each) operated at the PML site to simulate the full scale ASB operation. Following these incidences, it was evident that there is need for improved understanding and modelling of strategies to control cyanobacteria present in PML wastewaters.

The aim of the research reported here was to establish models that describe the dynamics of cyanobacteria presence, indicated by phycocyanin, in PML wastewaters when exposed to zinc. This was investigated based on the inhibitory effect of Zn on cyanobacteria. In this research, batch experiments were conducted using a strain of *Microcystis aeruginosa* (MA338) and *Pseudanabaena spp*. (naturally occurring) in samples collected from ASB wastewaters. Growth and inhibition of the cyanobacteria were assessed by fluorometric detection of phycocyanin (using an EXO1 sonde with EXO Total Algae PC Smart Sensor), which is a cyanobacterial specific pigment that increases linearly with cyanobacterial biomass increase.

Phycocyanin levels were determined for batch experiments where Zn was dosed at between 0.3 and 2.4 mg/L and in controls, for 7 days. At lower concentration (~0.3 mg/L), Zn was found to be supportive for the growth of MA338 based on phycocyanin data. In contrast, Zn $\geq$ 0.7 mg/L was found to be effective in suppressing the cyanobacteria tested in this study. For test samples (with Zn $\geq$ of 0.7 mg/L), two functions [exponential peak (EP) and logistic dose response (LDR)] were fitted to % phycocyanin vs time data. From the collected data at initial and on days 1, 3, 4 and 7, the phycocyanin reduction (decay) rates at the various Zn doses ($0.7 \leq Zn \leq 2.4$ mg/L) were determined. The reduction rates (Δ%Phy/Δtime) differ between the two models but trended consistently (EP: 52, 64, 85, 164 and LDR: 85, 249, 188, 1621 for Zn concentrations of 0.7, 1.1, 1.6 and 2.4 mg/L, respectively).

The two models broadly described the dynamics of phycocyanin levels in samples of PML wastewaters in response to Zn exposure up to 2.4 mg/L over 7 days. Both models differ in their fittings over the first few days to Zn exposure, where the EP model correctly describes an increase in phycocyanin after initial Zn exposure. However, the maximum level estimated by this approach is speculative of what is the true maximum value, and for this much finer resolution data would be needed over the early stage of batch experiments. Further investigation is needed to determine the Zn concentration with exposure time that would suppress or enhance cyanobacteria growth and the fate of Zn in PML ASB systems. Integrated modelling with phycocyanin monitoring has the potential to better implement strategies for cyanobacterial control, through rapid assessment of the responses and efficiencies of chemicals applied to inhibit cyanobacteria growth.

Keywords: *Microcystis aeruginosa, ASB, phycocyanin, dose response modelling*

Mixing assumptions and transit times using an age-ranked storage approach

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Abstract: The amount of time water spends in the subsurface is an important controller of stream water quality and is highly informative for understanding the activation of different flow paths. Water quality and hydrology have historically been modelled using separate approaches and the lack of a unifying theory to concurrently model water and solute transport has limited our knowledge of catchment functioning. Recent research has formulated catchment transport volumes with non-stationary travel time distributions (TTDs). This is achieved using an age ranked storage approach, where water enters storage through precipitation events and grows older until it exits either through streamflow or evapotranspiration. Each precipitation event is tracked in the age-ranked storage until all the water has been removed from storage. Outflows need to be assigned a sampling function (such as uniform, power-law, or beta distributions) that describes their age preference for water in storage. This relationship can be expressed as:

$$\frac{\partial S_T(T,t)}{\partial t} + \frac{\partial S_T(T,t)}{\partial T} = J(t) - Q(t)\Omega_Q(S_T(T,t),t) - ET(t)\Omega_{ET}(S_T(T,t),t) \tag{1}$$

where S_T is the age-ranked storage, J is precipitation, Q is streamflow, and ET is evapotranspiration. They are expressed as functions of their age T at time t, and Ω_Q and Ω_{ET} are the respective selection functions from storage.

Studies utilising this approach have generally been limited to wetter and energy poor catchments of the Northern Hemisphere. Here, we test different storage selection assumptions on the Corin Catchment, located in Namadgi National Park, ACT. Catchment losses to ET (708 mm/yr) are on average more than double values of Q (283 mm/yr). A beta sampling distribution was selected to investigate the effect of different mixing assumptions. Different combinations (n=190) of the beta parameters a and b were tested to examine the assumptions of uniform selection (a=1, b=1), preference of young ages for ET (a<1, b=1), and both young age (a<1, b=1) and old age (a=1, b<1) preference for streamflow. Parameters were incremented in units of 0.1 (e.g. a=0.1 to a=0.9, b=1 for young age preference for ET).

The mean MTT over the study period varied from 0.04 years to 3.84 years for Q and 0.07 to 1.16 years for ET across the different mixing assumptions (Fig. 1). The results highlight the potential lasting impacts of pollutants within this catchment and can provide water resource managers with an estimate of their longevity. One of the difficulties of this approach is that validation requires an observation of water age in the outflow. Conservative tracers, such as the stable isotope composition of water, or radioactive isotopes (tritium) are commonly used and will form part of our ongoing research into MTTs in the Corin Catchment.

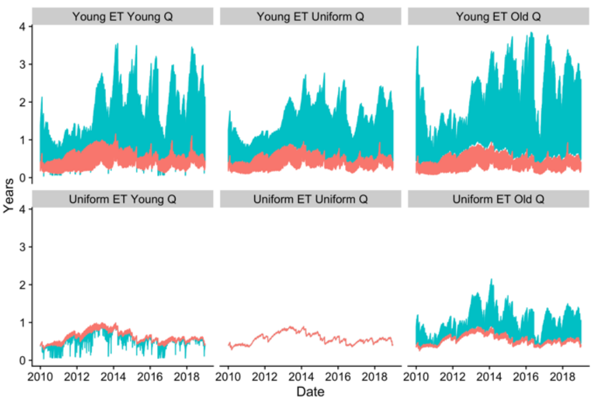

Figure 1. Mean transit time estimates for ET (red) and Q (blue) for the Corin Catchment using different beta distribution assumptions.

Keywords: *Catchment hydrology, transit time, travel time distributions*

An integrated catchment water quantity and quality modelling framework for Port Phillip and Westernport Catchments

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Abstract: Port Phillip (PP), Western Port (WP) and the waterways in the PP and WP catchments are highly valued by the communities living in these catchments. Policies, strategies, regulations and targets are currently in place to manage the quality of water flowing into PP and WP, and the inland waterways, such as the PP Environmental Management Plan 2017-2027, State Environment Protection Policy (SEPP) (Waters), Melbourne Water's Healthy Waterways Strategy (2018-2028) and Water for Victoria (e.g. Improved stormwater management and Integrated Water Management Programs).

As part of the evidence-base to support the development and revision of such policies and strategic planning, an integrated, multi-functional and flexible catchment hydrology and water quality modelling framework has been developed in eWater Source platform, that has been used to investigate:

- The impact of population growth (i.e. land use changes) and climate change on runoff (including wastewater) and pollutants discharging into waterways and marine environments
- Effective intervention options for pollutant load reductions
- The effectiveness of various policies and programs, and the extent of achieving targets
- Data gaps where there is no monitoring data or where the model would benefit from additional data

A significant challenge of the project was developing a modelling framework that represents the hydrology and pollutant export of highly modified catchments (e.g. channelized waterways and substantial river regulation) at large spatial scales (13,000 km^2 total catchment area) and was commensurate with the available data. The framework also needed to be of sufficient complexity to capture diverse hydroclimatic conditions, diffuse pollutant loads from a diverse range of land uses, point-sources such as sewage treatment plants and both existing and potential integrated water management practices. The presentation discusses some of the specific challenges faced during model development including representation of integrated water management practices, and the solutions that were derived.

The model has been useful in providing an indication of how pollutant and flows will change into the future (ie, how bad is it going to get if development occurs unmitigated) at a regional scale, and testing catchment intervention strategies, such as:

- Alternative best practice flow and pollutant targets,
- Understand the impact of new stormwater management amendments in Victorian Planning Provisions
- Returning priority areas within urban or urbanizing catchments to a more natural hydrology,
- Improving performance of stormwater harvesting wetlands,
- The effectiveness of rural land program initiatives

Keywords: *Integrated catchment modelling, water quality, integrated urban water cycle management, stormwater management*

Application of a dynamic sediment budget model (dSedNet) in the Westernport catchment

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Abstract: Western Port, Victoria, supports a diverse range of aquatic animals such as waterbirds, fish, marine invertebrates and mammals and is of international significance (e.g. UNESCO Biosphere Reserve, Ramsar convention listing for migratory waterbirds), as well as containing 3 of Victoria's 13 marine national parks. Catchment sediment supply has been identified as a major impact on water quality in the bay and has been implicated in the loss in large areas of critical habitats, most notably intertidal seagrasses since the 1970s. As part of understanding the current condition of waterways, the trajectory of major threats and management opportunities, Melbourne Water has initiated a range of catchment and marine monitoring and research programs since the early 2000s. In the Westernport catchment, rural activities, urban growth and coastal erosion have been associated with high sediment loads. Based on previous sediment studies, a sediment load target of less than 28,000 tonnes per year to Western Port was recently incorporated into the Victorian State Environment Protection Policy (Waters) (SEPP).

Recognising the need to understand the most cost-effective strategies for managing sediment loads to Western Port, a dynamic sediment generation and transport simulation model is a valuable tool. The model is useful for integrating data and knowledge of catchment processes, and provides a framework from which to explore catchment intervention options to reduce sediment export to Western Port and achieve the SEPP target.

This presentation outlines the implementation of a time-stepping, spatially-distributed sediment budget model (dSedNet) to the Westernport catchment to predict daily sediment loads under various catchment intervention scenarios. CSIRO's dSedNet model supports the exploration and calibration of sediment transport at the reach-to basin scale, and has been integrated into Australia's national hydrological modelling platform (Source). Source-dSedNet is a collection of models that can be applied to Source's Geographic scenario elements - Functional Units (areas of similar hydrology and sediment generation), Nodes and Links. For each Functional Unit (e.g. landuse) or Link in the network, the model constructs daily budgets of fine and coarse sediment that are transported to the catchment outlet. Erosion rates (hillslope, gully and streambank erosion), and fine and coarse sediment sinks (floodplains and reservoirs) are disaggregated from mean annual rates, based on daily rainfall and runoff. In the Westernport catchment, the proportioning of these sources is important, as the understanding of which sediment sources are likely to be contributing to the receiving environments needs to be well understood in order to effectively target appropriate management actions.

In developing the catchment model, the following key opportunities and outcomes will be discussed in the presentation:

- Aligning the Westernport catchment model to components of the existing regional Port Phillip-Westernport catchment model, developed over a number of years by Melbourne Water, the Victorian Department of Environment, Land, Water and Planning and EPA Victoria, to ensure consistency in terms of hydrology, catchment boundaries, climate and land use.
- Improved spatial and temporal data parameterisation functionality, including the ability to add temporal variation to vegetation cover to mimic seasonal change in % cover,
- Calibration of sediment load for the four major systems (Bunyip River, Bass River, Lang Lang River, and Cardinia Creek). The dSedNet model was able to achieve a good estimation of mean annual loads, the excepted distribution of loads from key sources (i.e. streambank erosion as the dominant process in line with other studies), and the majority of high erosion events generated during peak flows.
- The Catchment Planning Tool developed as a web-based decision support 'front-end' to the Westernport model, presents model results at various temporal and spatial scales to support long-term catchment planning.

Keywords: *Integrated catchment modelling, water quality, sediment erosion, dynamic SedNet*

Modelling nitrogen transport in sugar cane from soil to runoff from banded surface and buried fertiliser using HYDRUS2D and a post-processing algorithm

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Abstract: Simulated rainfall was applied to sugar cane at the Macknade Research Station, Herbert region North Queensland, to determine the loss of nitrogen to runoff for fertiliser placed in a 100 mm wide strip on raised beds (spaced 1.8 m apart and a bed width of 1.2 m) applied either on the surface or buried at a depth of 50-150 mm. The sites were covered with shelters between rainfall simulations to avoid rainfall ingress, but evaporation could still take place. Modelling of these experiments was untaken to estimate nitrogen losses from recently fertilised soils in wet tropical catchments. The model parameters can be used to model other possible runoff scenarios. The modelling required a two-dimensional model with multiple solute species transport and chain reaction processes. The HYDRUS2D model (Simunek et al., 2012) was chosen; however, it cannot model the transfer of solutes to the runoff water. An analytical model, which can transfer of solutes to runoff was developed by Wallach and van Genuchten (1990):

$$J(0,t) = -\theta_s k\left[c(t) - c_r\right] \tag{1}$$

where J(0,t) is the flux density of solute transferred from the soil surface to the runoff water [M L^{-3} T^{-1}] at time t [T], θ_s is the saturated volumetric water content at the soil surface [L^3 L^{-3}], k is the mass transfer coefficient [L T^{-1}], $c(t)$ is the concentration at the soil surface with time [M L^{-3}] and c_r is the concentration in the runoff water [M L^{-3}], which we set to zero as Wallach and van Genuchten (1990) did. A post-processing method to compute the solute transport of nitrate, nitrite and ammonium to the runoff using eqn (1) was developed. This required surface concentrations of the solutes with time in a cross-section across the bed ($c(x,t)$ where x is the cross-section distance) and integrating both with space to give the mass transfer at time t_i, $M(s,t_i)$, using:

$$M_i\left(s,t_i\right) = \int_0^{x_n} -\theta_s c(x,t_i)dx \approx \theta_s \sum_{j=0}^{n-1}\left[c(x_{j+1},t_i) + c(x_j,t_i)\right]\left(x_{j+1} - x_j\right)/2,\ \ s = \sum_{j=0}^{j-1}\left(x_{j+1} - x_j\right) \tag{2}$$

and this was then integrated with time to give the mass transferred during the runoff:

$$M_T = k\int_0^T M_i(s,t_i) = k\sum_{i=0}^{m-1}\left[M_{i+1} + M_i\right]\left(t_{i+1} - t_i\right)/2,\ \ T = \sum_{i=0}^{m-1}\left(t_{i+1} - t_i\right) \tag{3}$$

where s is the length of the runoff surface [L]. The parameters in the model were adjusted to obtain the best fit with no fertiliser treatment experimental values. These values were used to model surface-applied and subsurface applied fertiliser. The results are shown in Table 1. The infiltration rate following the first rainfall was halved, so simulations were performed with saturated hydraulic conductivity of layer 1 halved.

Table 1. Modelled (MO) and measured (ME) DIN (NH_4-N and NO_x-N) losses in runoff two fertiliser treatments. Simulations with saturated hydraulic conductivity (Ks(1)) halved are also shown.

Soil layer 1	Surface				Subsoil			
	NH_4-N (kg ha^{-1})		NO_x-N (kg ha^{-1})		NH_4-N (kg ha^{-1})		NO_x-N (kg ha^{-1})	
	ME	MO	ME	MO	ME	MO	ME	MO
Ks(1)	0.73	0.09	1.32	0.98	0.12	0.03	1.39	0.84
Ks(1)/2	0.73	0.98	1.32	1.29	0.11	0.03	1.39	1.80

Keywords: *Runoff, nitrogen, HYDRUS2D, hybrid model*

Coupling a simple groundwater model to surface water for steady state contaminant transport

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Abstract: Increasing nitrogen (N) concentrations in fresh waters are impacting adversely on New Zealand's environmental and economic resources. We have previously developed a quasi-distributed model based on contaminant budgets for all of New Zealand, called CLUES (Catchment Land Use for Environmental Sustainability). While the model runs quickly, it does not have an explicit component to account for groundwater transport. We therefore extended CLUES to incorporate conceptual groundwater reservoirs under each model subcatchment, and trialed the extended model in two case studies. The resulting model, CLUES-GW, provides mean-annual contaminant load and concentration estimates for surface water. CLUES-GW includes up to two groundwater reservoirs under each surface water sub-catchment. They might, for example represent shallow unconfined groundwater and a deeper aquifer under each subcatchment. The groundwater reservoirs exchange water and contaminants laterally with the adjacent (groundwater) reservoirs, enabling groundwater transport across surface water subcatchment boundaries. The shallow reservoir also exchanges water with the surface-water streams. Each of these outflows from a reservoir is characterized by an exchange coefficient representing the proportion of the total inflows that follow that pathway. With linear decay, the system forms a linear steady-state set of equations which can be solved with matrix algebra. The runtime of the model is approximately 4 seconds, and so the quick runtime allows extensive model calibration, uncertainty and scenario analyses. The model was applied to two case study catchments to investigate N transport. In both cases a separate groundwater flow model was used to assist with establishment of the lateral and vertical exchange coefficient of the model. The first catchment, Hauraki is located within the Waikato region of New Zealand and consists of 7,295 sub-catchments. Monte Carlo parameter conditioning from 10,000 parameter realisations was used to identify the best 200 'posterior' parameter sets using PEST^{++} software. The posterior parameter distributions were used to examine the N loads and concentrations at key locations under the current N loading dynamics and a hypothetical future scenario of 20% reduction in N loading. The second catchment, Mid-Mataura in the Southland region of New Zealand, is smaller and has 1,535 sub-catchments. The model was calibrated using PEST software against measured river flows, and N loads and concentrations. An approach was developed to disaggregate model outputs, of mean-annual contaminant loads and concentrations, to daily timesteps using a rating-curve relationship between measured flows and concentrations. The calibrated model output, along with the relationships developed for disaggregation were used to develop daily N concentration timeseries using flow data. The new methods enable extension of the current CLUES model to include groundwater explicitly, so that groundwater attenuation can be considered in scenarios of the effects of land use and management on water quality.

Keywords: *Surface-groundwater model, Nitrogen, catchment*

Estimating bankfull channel geometry, dimensions and associated hydraulic attributes using high resolution DEM generated from LiDAR data

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Abstract: Knowledge on river channel dimensions at bankfull flow is essential for flood forecasting, stream rehabilitation and bank stabilization works, environmental flow modelling, and streambank erosion modelling. The difficulty of collecting spatially distributed, high-resolution data on channel form and behaviour made it necessary for broad scale erosion models to adopt generalised approaches to bankfull flow estimation. These techniques are commonly based on simple hydraulic formulae applied to cross-sectional averages. It is recognized that these generalised estimations frequently fail to describe the non-uniform flow and transport conditions observed in natural rivers. Application of Dynamic SedNet in the catchment water quality modelling project of Paddock to Reef Integrated Monitoring, Modelling and Reporting Program (P2R) under Reef Plan uses relationships between channel width and height with contributing catchment area that are regionally generated to determine these river channel dimensions. There are obvious shortcomings of this approach including: (1) the fact that channel dimensions are greatly spatially variable even when values of the explanatory variable are the same (e.g., bankfull flow occurs more often on coastal plains), (2) limited data points used to generate the empirical equation. However, with recent advances in the area of generating high resolution digital elevation models (DEMs) from Light Detection And Ranging (LiDAR) data and availability of tools to process them, it may be possible to determine channel geometry and dimensions in a more robust and reliable way. Conventional topographic LiDAR, such as that used to generate the DEM used in this study, does not penetrate water bodies. In these situations, water penetrating LiDAR (Bathymetric LiDAR) will need to be employed. However, in low flow situations, as in the current study, and/or where flow depth can be determined from monitoring, it is possible to subtract flow depth from the water surface elevation to estimate channel-bed elevation and height.

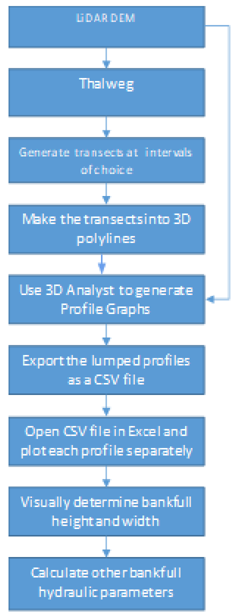

Figure 1. Workflow for estimating river channel dimensions from LiDAR DEM

This study demonstrates how a high resolution DEM generated from LiDAR data in conjunction with estimates of flow depth, which was low at the time of LiDAR data acquisition, can be used to generate bankfull river channel width and height thereby allowing estimation of other river flow parameters. Figure 1 shows the workflow (steps followed) in order to achieve this.

Bankfull flow parameter values estimated from the approach currently employed in P2R and those estimated in this study (e.g. flow cross-sectional area, wetted perimeter, and hydraulic radius) have been compared at two modelled stream reaches where LiDAR DEM is available. The comparison shows that the P2R approach overestimates all bankfull flow attributes. However, since Dynamic SedNet uses a user-specified recurrence interval to determine bankfull discharge and applies a calibration coefficient for adjusting bank erosion, the model may not necessarily overestimate streambank erosion. Nevertheless, the reliance on a calibration coefficient to account for input data limitations reduces confidence in model predictions, as it could lead to situations where the model gives the right answer for the wrong reason which will inhibit parameter transfer outside the calibration dataset.

This paper has: (1) demonstrated that the approach adopted in this study using LiDAR DEM may be a more reliable alternative than determining river channel dimensions as a power function of catchment area, and the application of the concept of recurrence interval in estimating bankfull flow, and (2) shown that the assumption of rectangular river channel geometry in the application of Dynamic SedNet in P2R is overestimating bankfull flow and associated hydraulic attributes such as hydraulic radius in the case study reaches.

Keywords: *Channel dimensions, Dynamic SedNet, hydraulic parameters, Mary Catchment*

What do we need from catchment water quality models in Australia?

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Abstract: The published literature on the development and investigations into water quality modelling has primarily focused on making better predictions. Few studies have actively reported on model user needs and the implications of these needs on designing and selecting models that are fit-for-purpose. This paper describes the results of a Water Quality Model Needs survey that targeted persons developing or using models for catchment-scale Australian applications (Figure 1). Some 106 survey responses were received and analysed. Suspended sediment, total phosphorus and total nitrogen were highlighted by respondents as the most important constituents for catchment water quality models. The top five important drivers or management options were land use change, flow management, riparian management, climate change and point source control. Tool functionalities such as easy to include additional processes, output reporting, sensitivity analysis, and easy to access, use and learn were consistently identified as the most important features for catchment water quality models.

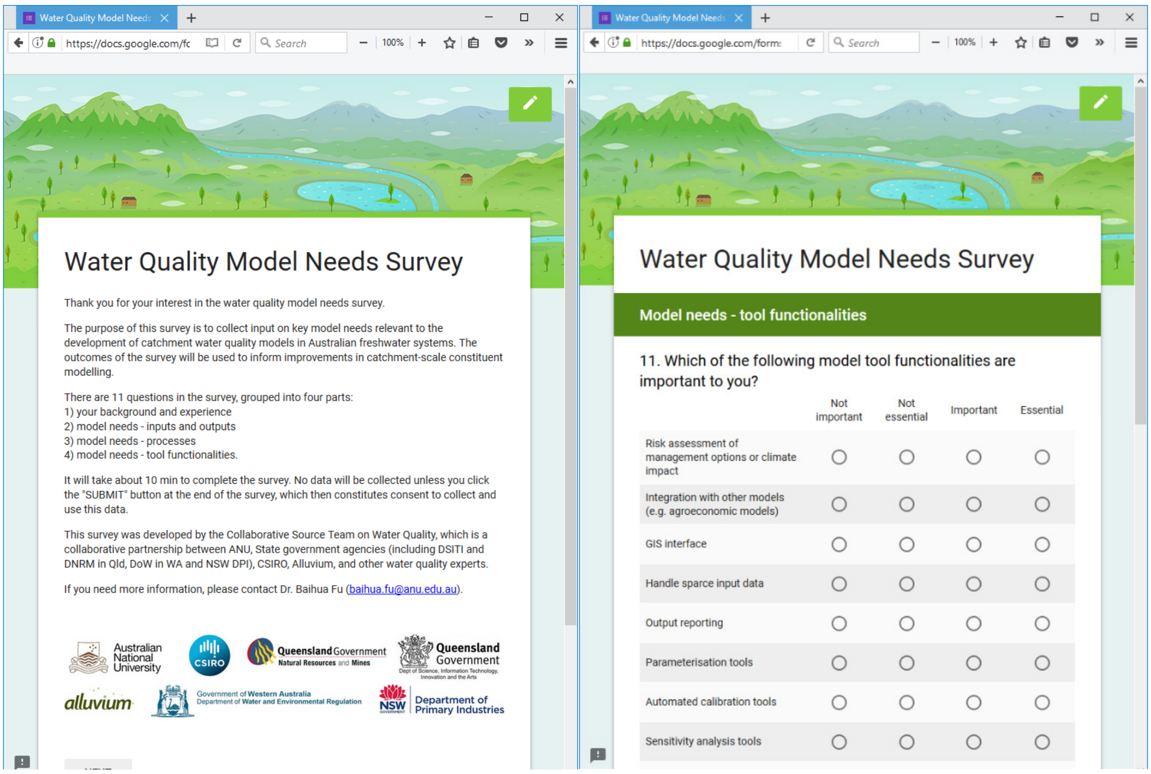

Figure 1. Screen shots of the online Google Forms survey

Keywords: *Water quality modelling, catchment management, users, stakeholder needs*

Developing a hybrid water quality model to support catchment management

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Abstract: Water quality models are increasingly used to support catchment management. Broadly, two types of models are commonly available, largely based on model complexity. At the simpler end of the spectrum are the statistical models (e.g. ANN, Kriging methods) and linear (including transformations) regression models (e.g. Event Mean Concentration). While these types of models are simple in structure and may require only a small amount of data to apply, they provide little understanding and representation of the catchment processes (including management) at play. At the other end of the complexity spectrum are process-based models. Examples are HSPF, SWAT and INCA. A significant amount of attention has been given to the development and improvement of these models internationally. However, these models often have intensive data, calibration and uncertainty assessment requirements.

To address this gap in model complexity, we have developed a prototype hybrid networked-empirical water quality model for nutrients that includes important inputs associated with key variables associated with nutrient generation, land-to-water delivery and transport processes. The model structure is inspired by SPARROW (Schwarz et al, 2006), but is modified to fit the eWater Source framework (Carr and Podger, 2012) and to include temporal dynamics of the system by introducing soil and groundwater stores. A Source plugin is being developed to implement the model. The project involves three case study catchments: Vasse Catchment in WA, Wet Tropics Catchments in Qld and Richmond River Basin in NSW.

This presentation provides an overview of the model, using the Vasse Catchment as a case study. The Vasse model retains the Source node-link structure, but with more detailed modelling at the Functional Unit (FU) level, and some modification at the link level. At the FU level, each FU is conceptualised with various nutrient sources. Each source has its own land-to-water delivery component represented by an exponential function of the various variables contributing to the delivery of the source nutrient to waterways. For the Vasse model, sources of nutrients considered include fertiliser, feed, clover fixation, septic tank, dairy effluent, plant decay, atmospheric deposition, and erosion. Factors contributing to land-to-water delivery include runoff, drainage, groundwater discharge, soil phosphorus-binding potential, riparian vegetation, soil moisture and temperature. At the link level, it is possible to use the Source in-built first-order decay function, or an exponential function of variables relating to the transport and attenuation of nutrients, here being flow and travel time. Preliminary model results are discussed. The development of this model (and associated eWater Source Plugin) will provide end users with an alternative modelling approach which will improve representation of constituent generation and land-to-water delivery processes, whilst balancing the number of data required to build and run the model.

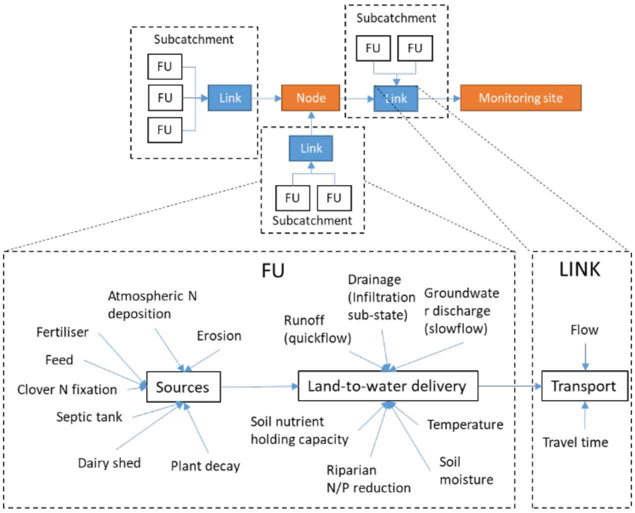

Figure 1. Conceptual diagram of the model

Keywords: *Water quality, catchment management, Source, spatially distributed*

A Source plugin to predict and prevent hypoxic blackwater risks in floodplain-river systems

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Abstract: Hypoxic blackwater events can occur following inundation of river floodplains and cause severe impacts on aquatic ecosystems. The inundation of organic matter on the floodplain results in dissolved organic carbon (DOC) being released into the water, and the microbial decomposition of this carbon consumes dissolved oxygen (DO). To represent this process, a DO-DOC plugin has been developed in the Source hydrological modelling software to inform risk mitigation strategies to prevent or minimise the occurrence and intensity of hypoxic conditions. Key functionality of the plugin includes representing plant litter build up and degradation across the elevation gradient on the floodplain, leaching of DOC from this litter when inundated, DO consumption arising from microbial decomposition of the DOC, and reaeration processes (including water flow over structures). The model is configurable on both river channels and floodplains (links) and lakes (storages), and the DO and DOC constituents can be simulated along the full length of a Source catchment model. The DO-DOC model plugin is freely available as part of the Source installation; instruction and source code for the plugin and the reference to the DO-DOC model is available online.

The plugin was parameterised to represent a 100 km study reach in the River Murray in South Australia to simulate DOC (R^2= 0.84 - 0.93) and DO (R^2=0.74 - 0.92 for main channel sites) (Figure 1). Following calibration, a number of scenarios were tested to inform potential future operation of environmental regulators, structures designed and constructed on the floodplain to create floodplain inundation at flows substantially lower than would otherwise be required. The scenarios were designed to test the sensitivity of model outputs to key parameters (rate of inundation, temperature, litter load, reaeration coefficient) and help develop strategies to minimise the likelihood of triggering hypoxic blackwater events. The development of the plugin provides an example of representing complex water quality processes in Source, and the ability to simulate a range of management scenarios to assess and minimise risk of hypoxic blackwater events is demonstrated.

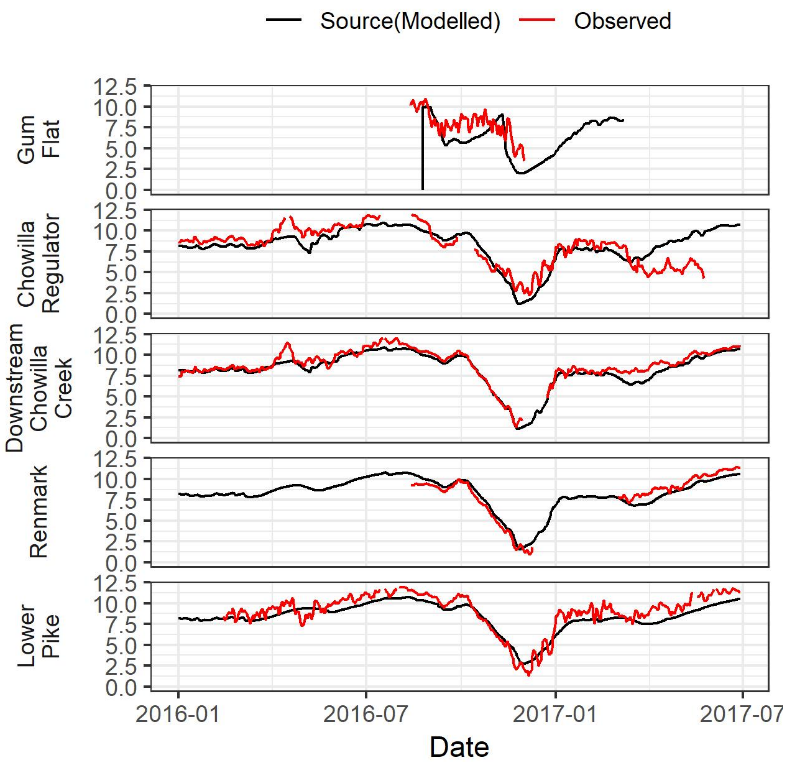

Figure 1. Modelled and observed dissolved oxygen (mg.L^{-1})

Keywords: *Hypoxia, dissolved organic carbon, Murray-Darling Basin, eWater Source, Constituent plugin*

Future Water: Comparing and contrasting approaches to predicting water quality

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Abstract: Globally, surface water quality deterioration is an important issue exacerbated by increasing urbanisation, intensified agricultural activities and climate change. To mitigate this increase in waterway pollution there is a strong need for effective catchment management strategies. However, this is currently limited by: (1) our lack of understanding of the key processes and mechanisms driving water quality change in waterways, and (2) our inability to predict future water quality change. To address these, we need to improve our ability to understand and model water quality. This improved capacity will enable us to better identify important water quality changes under various land use, land management and climate scenarios. These improvements could thus assist waterway managers to better prioritise regions which require special management attention, as well as better assess the benefits of different management interventions and preventative actions to reduce pollution levels.

Given the above, there is a vital role for predictive models for supporting catchment water quality management. There is a wide spectrum of surface water quality modelling approaches, ranging from purely black-box empirical to detailed process-oriented models; these often have contrasting strengths and weaknesses. This study aims to (1) provide a review of key considerations for designing and developing effective modelling approaches for water quality prediction; and to (2) outline reasons for choices in modelling approaches for rural and urban water quality across Victoria. A fundamental consideration is the modelling purpose which provides preliminary guidelines for other modelling decisions. The core decision in modelling water quality is the conceptualisation of key physical processes, which involves the definition of pollution sources, flow/transport pathways and other catchment features. In addition, practical considerations such as data availability and model development effort are also important. For each consideration we provide recommendations for different types of catchments, and specifically highlight distinctions between natural/rural and urban catchments.

We illustrate these considerations with two modelling approaches: a) a data-driven statistical approach informed by conceptual understanding and b) a more process-oriented approach. These models have been applied in rural and urban settings respectively. Both approaches are designed to identify spatio-temporal differences in water quality, and to predict how future water quality will change. Being designed for vastly different environments (rural vs urban), these two models present separate, yet parallel approaches for modelling spatio-temporal variability in water quality. By contrasting these models, we aim to highlight strengths and weaknesses of different approaches, to share practical experiences from implementing these approaches and to identify the ways forward for both approaches. The experiences and recommendations from these modelling approaches can provide valuable recommendations to assist future water quality modelling works to identify effective modelling approaches.

Keywords: *Water quality modelling, urban catchments, rural catchments, sediments, nutrients*

National scale nutrient/metals loading model - VEMALA

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Abstract: The operational, national scale nutrient loading model, VEMALA, has been developed for water quality (nutrients, metals) simulations and scenarios for Finnish watersheds (Huttunen et al., 2015, Korppoo et al., 2017). It simulates nutrients and heavy metals processes, leaching and transport on land and in rivers and lakes. VEMALA simulates nitrate, ammonium, organic nitrogen, phosphate, particulate inorganic phosphorus, organic phosphorus, phytoplankton, suspended sediments and total organic carbon, as well as heavy metals (zinc, nickel, copper etc.) in the aquatic ecosystem. VEMALA is applied for real time simulation and forecasting of water quality, including forecasts for chlorophyll-a concentration and the main results are provided to the public.

Hydrological simulation is based on the WSFS system (Vehviläinen, 1994), which simulates the hydrological cycle on a one-day time step using standard meteorological data. The system covers the whole land area of Finland, including cross-border watersheds, total of 390 000 km^2. About 40 000 lakes larger than one hectare are simulated. For phosphorus and nitrogen leaching and erosion simulation, the field level ICECREAM model is applied (Figure 1). In the ICECREAM model, farming practices, fertilization, crop growth, phosphorus and nitrogen cycle in the soil and finally leaching and erosion are simulated on a daily time step. Point loads, atmospheric deposition and load from settlements are included in the model. For natural background leaching and loading from forestry, estimated values are used. A biogeochemical model (Korppoo et al., 2017) is used to simulate nutrient processes in rivers and lakes. VEMALA predicts the co-impact of dissolved inorganic nitrogen and phosphate on algal growth and therefore on eutrophication.

The VEMALA model is applied for load reduction and country-wide climate change scenarios. Simulation of bioavailable nutrients rather than total nutrients allows the distinction in the quality of the various loading sources, farming actions and loading reduction actions under present or climate change scenarios to help water managers implement the Water Framework Directive in Finland. VEMALA is used e.g. in the BlueAdapt project (https://blueadapt.fi/en/project-info/) at various scales to simulate the nutrient loading to rivers, lakes or to the Baltic Sea.

The VEMALA model is also used as a new assessment method for water management in the mining industry. The biotic ligand model PNEC Pro v6 (Predicted No-Effect Concentration) describing the safe dissolved metal concentrations is implemented within VEMALA to be compared to the simulated concentrations in the water for nickel, copper and zinc. Nickel concentration simulation over the period 08/2012-12/2018 in Kivijoki river, downstream of a mine after an accidental leak in November 2012, is well represented with a Nash and Sutcliffe Efficiency coefficient (NSE) for nickel concentrations of 0.49 (Figure 2). VEMALA provides up-to-date information on the impact of a mine, in the aquatic ecosystem downstream, under normal discharge or exceptional emissions from a mine with current or forecasted water conditions.

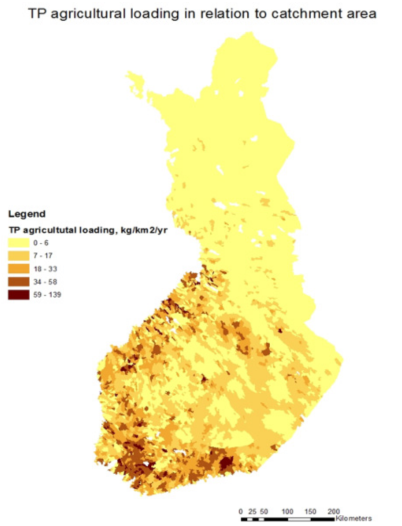

Figure 1. Areal total phosphorus agricultural loading in Finland (kgP.km^{-2}.yr^{-1})

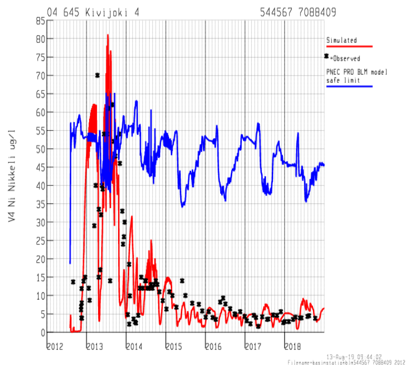

Figure 2. Nickel concentration (µg.L^{-1}) in river Kivijoki (Finland) observed (black dots), simulated by VEMALA (red line, NSE=0.49) and the nickel PNEC (blue line) downstream a mine

Keywords: *Water quality model, national-scale, Water Framework Directive, mining effect*

Modelling the canopy effect in filamentous algae mats

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Abstract: For decades, nutrient-driven nuisance algal growth has wreaked havoc in the lower four Great Lakes. Empirical and mechanistic models have long been used to set offshore nutrient targets and manage nutrient loads to meet those targets. Although there was some success in mitigating nuisance algal growth, ecosystem perturbations in the last two decades have resulted in a *Cladophora* resurgence. We offer improvements in the mechanistic Great Lakes Cladophora Model in version 3 (GLCM v3) to better inform management. Like earlier versions (GLCM v1 and v2), the model simulates algal biomass density (g dry mass m^{-2}) and stored (cellular) phosphorus content (P as % dry mass) over the growth period. Earlier versions of the GLCM treated the algal mat as a lumped system, using the logistic growth model with a prescribed maximum biomass density coefficient to simulate the carrying capacity effect. While that approach resulted in good agreement with biomass observations (normalized root mean square error, NRMSE =17.8%, and percent bias, PBIAS = -11.0%), it was not based on identified ecological mechanisms. As such, empirical specification of the coefficient was undermined by significant intra- and inter-site variability. Two major advances are presented: 1) an improved characterization of the light and temperature response surfaces driving photosynthesis and respiration and 2) a segmented canopy approach for simulating the effect of self-shading (carrying capacity) on growth. In the GLCM v3, biomass accrual is mechanistically governed by light attenuation through the canopy and model agreement with observations improved (NRMSE = 13.6%, PBIAS = -5.7%). The introduced vertical extinction coefficient for light passing through the mat included in GLCM v3 may be directly measured and offers much less freedom as a tuning parameter than the prior approach using a maximum biomass coefficient. The GLCM v3 is a more mechanistic and robust tool than previous versions, designed to aid management of nuisance algal growth.

Keywords: *Mechanistic model, filamentous algae, periphyton, canopy, shading*

Identifying faecal contamination sources and assessing mitigation effectiveness in a drinking water catchment

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Abstract: Agricultural activities have the potential to contribute a range of faecal microbes to waterways that can reduce water quality in drinking water supplies and require efforts to manage key pollutant sources and levels of water quality treatment. Molecular microbial analysis and reference databases paired with Bayesian models can provide catchment managers with vital information to manage these risks.

The Tarago Reservoir supplies potable water via the Tarago Treatment Plant to residents of south-east Melbourne. The catchment contains several potential sources of faecal pollution, including grazed agricultural operations, dominated by dairy and beef cattle, along with rural-residential development utilising on-site wastewater disposal. The catchment also contains production forest and reserve land, which supports several native and introduced wildlife such as wombats, wallabies and deer. Faecal pollution may enter waterways through direct deposition by animal defecation, or transport via overland and subsurface flow. Within the catchment, riparian buffers have been established around streams on agricultural land, with the intention of excluding direct deposition and improving the quality of runoff bearing cattle faecal material.

This study aims to identify the primary sources of faecal pollution within this catchment and assess the effectiveness of these pollution mitigation measures using SourceTracker, a Bayesian source apportionment tool that can be used to understand faecal water pollution by determining the proportional contribution of sources of faecal pollution within a sink environment (any receiving waterbody). To achieve this aim, water samples were collected during both dry and wet weather from the reservoir, as well as two major and 12 minor tributaries; representing the pollutant 'sinks'. Faecal scats were also collected from the catchment area to serve as regionally-specific 'source' samples and combined with an existing regional faecal source library to make a total of 263 scats from a range of host sources. Total genomic DNA was extracted and 16S and18S rRNA amplicon sequencing conducted using Illumina MiSeq with previously optimised conditions. Data were processed for analysis using the QIIME2 v2019.1pipeline with source contributions predicted using SourceTracker v2 under default parameters.

The results demonstrate that contribution of faecal contamination was highest in small agricultural streams, followed by the agriculture-dominated major tributary, then the forest-dominated major tributary and the reservoir. Results suggest that wild animal sources dominated at all sites. Within-category variability of source contribution to waterways was largest for buffered catchments, which may reflect the variability of habitat (for example canopy or understory vegetation of different levels of maturity) supplied by riparian buffer zones when compared with unbuffered streams, environments which are dominated by pasture grass. Though wild animals contributed the largest proportion at all sites, contribution from agricultural faecal contamination formed a higher proportion in unbuffered catchments than buffered catchments. This is consistent with the exclusion of stock animals from stream channels within the catchment, areas where daily average grazing intensities can be high (up to 18 cows.ha^{-1}). These results indicate that exclusion of stock from riparian areas is likely to improve microbial water quality, and highlights the value of SourceTracker as a tool to aid environment and public health professionals understand the proportional contribution of faecal sources.

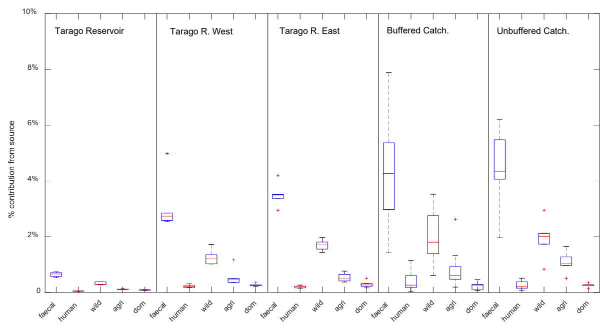

Figure 1. SourceTracker estimates of percent contribution of different sources to waterbodies within the Tarago Reservoir Catchment.

Keywords: *Bayesian, microbial source tracking, agriculture, SourceTracker*

Source Catchment Model application to assess outcomes for stream sediment loads from NRM Investment in Southern Inland Queensland

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Abstract: Australia has invested $10Billion in Natural Resource Management (NRM). A significant part of this investment was through Regional NRM groups aiming to target investment towards regional priorities. Reviews of NRM investment have repeatedly documented activities and outputs but have struggled to demonstrate outcomes. Remote sensing data has been used to quantify improving trends in ground cover in the Upper Maranoa River catchment in Southern Inland Queensland. This is a catchment dominated by grazing lands that have received Regional NRM group support since 2004. Prior to 2004, there was NRM support across the catchment delivered through Landcare.

This study used ground cover trends and reference data to synthesize ground cover for four scenarios approximating grazing land management practices for 1990, 2004, 2017 and 2050 (aspirational). The synthesised ground cover rasters were used to generate RUSLE c factors to input into a *Source* catchment model. The model was run for each scenario with the same climate data and other inputs for a model run period from 1986 to 2017. The scenarios provided estimates of changes in hillslope erosion due to changed grazing land management.

The 1990 scenario provided estimates of likely stream sediment loads if 1990 management practices were in place. The 2050 scenario provided estimates of the "aspirational" or best possible ground cover incorporating climate variability during the period. The 2004 scenario provided estimates of the progress towards the aspirational values during the Landcare period. The 2017 scenario provided estimates of the progress towards the aspirational values during the Regional NRM period.

Results indicate that during the Landcare period, 10% of the possible reductions in hillslope erosion were achieved. During the Regional NRM period, a further 15% of the possible reductions were achieved. In total this means that 25% of the possible reductions in hillslope erosion in grazing lands of the Upper Maranoa catchment were attained. This amounts to an average of 3,000 tonnes per year less stream sediment in the Maranoa River downstream of Mitchell. Although this is not all due to NRM investment, it does demonstrate outcomes at a local to regional scale. The aspirational values also provide an objective reference for ongoing work in sustainable landscape management.

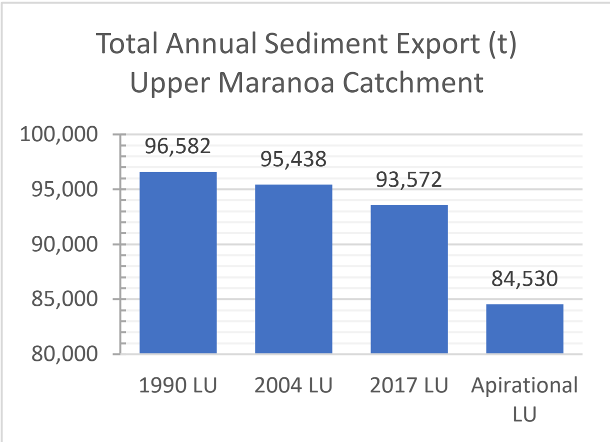

Figure 1. Average annual sediment load estimates for the Upper Maranoa catchment for different land use (LU) scenarios

The synthesis of seasonal ground cover data for different land use scenarios provides a mechanism for NRM staff to contribute to evaluations using the established eWater Source catchment model. This provides opportunities for broader application to evaluate NRM programs, to prioritise NRM investment and to quantify stream sediment load targets for local water quality guidelines.

Keywords: *Regional Natural Resource Management, eWater Source, Queensland Murray-Darling, grazing land management, groundcover*

EXTENDED ABSTRACT ONLY

Modelling the impact of design and operational variables on stormwater biofilter performance – a data driven approach

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Abstract: Stormwater biofilters, also known as rain gardens and biorientation systems, are most widely used Water Sensitive Urban Design technologies for urban stormwater management. Water quality treatment by stormwater biofilters is driven by complex physical, biological and chemical processes. As such, pollutant removal by biofilters is influenced by a large number of factors including operational variables (*e.g.* climate, rainfall characteristics, infiltration rates) and system design characteristics (*e.g.* plants, media type, filter depth). Over the past decade, extensive laboratory-based column studies have been conducted to investigate the water quality treatment performance of biofilter systems. This has led to a wealth of treatment performance data set, which provides a unique opportunity to develop a data-driven understanding of the key design characteristics and operational variables that affect biofilter treatment performance. This study used a Bayesian hierarchical modelling approach to develop statistical models to better understand the key drivers of system performance and predict outflow pollutant concentrations using both operational and design variables.

In this study, extensive monitoring datasets of the treatment performance of stormwater biofilters were collated. The datasets consist of four large comprehensive laboratory column experiments, with experimental results previously published by the authors. We focused on two pollutants that are of key concern in urban stormwater– TN (total nitrogen) and TP (total phosphorus). Statistical analysis, e.g. Principal Component Analysis (PCA) and correlation analysis were first performed to understand the relationships between all variables, with also an aim of reducing the number of variables used in the statistical modelling. Two Bayesian hierarchical linear regression modelling structures were used to evaluate the significance of key design characters and operational conditions on the outflow concentrations:

Model 1 – assumes that outflow concentration at time *i* for design j ($C\_out_{i,j}$) is modelled as a linear function of operational variables (antecedent dry weather period – ADWP, inflow concentration – *C_in*, *etc.*), with the regression coefficients (a_j, b_j, etc) determined by the design characteristics of each system (e.g., Vegetation Type, Media Type)	$\boldsymbol{C\_out_{i,j}} = a_j \times ADWP_{i,j} + b_j \times C\_in_{i,j} + ..$ $a_j = f(VegType, MediaType\ldots)$ $b_j = f(VegType, MediaType\ldots)$
Model 2 – same structure to Model 1 but with the design parameters being the main variable in the linear function, while the operational conditions determine the regression coefficients	$\boldsymbol{C\_out_{i,j}} = a_i \times VegType_{i,j} + b_i \times MediaType_{i,j} + ..$ $a_j = f(ADWP, C\_in\ldots)$ $b_j = f(ADWP, C\_in\ldots)$

The main preliminary findings of this study include:

- The key variables found to be highly impactful on outflow concentrations include operational conditions (inflow concentrations and flux, infiltration rate, solar energy and ADWP), and design parameters (vegetation type, filter media type and depth, and submerged zone presence).
- Both models had good performance, with highest Nash-Sutcliffe coefficients (NSE) for TP being 0.53 and 0.57 for Model 1 and Model 2 respectively; maximum NSE values observed for TN were 0.44 for Model 1 and 0.44 for Model 4.

The modelling results demonstrate that both operational conditions and system designs are important to predict stormwater biofilter performance accurately.

Keywords: *Bayesian hierarchical modelling, TP, TN, operational conditions, WSUD*

Complementing observed and modelled streamflow for Northern Australia – evaluating streamflow estimates from two hydro-meteorological operational models

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Abstract: Access to accurate near-real time and forecast information on freshwater influx in river system is vital for many users, for example water managers and operators or water policy makers. Applications using streamflow data are manifold including the need to forecast and produce warnings for floods, managing water rights, operating water for irrigation and power production as well as estimating freshwater influxes to surrounding to marine waters. To support these needs, centralised streamflow data repositories have greatly advanced over recent decades. However, streamflow gauges are rarely available across all areas of interest. In addition, gauges can also suffer from missing streamflow data or inaccurate measurements during large floods. This is a particular problem in Northern Australia where access to gauges during floods to improve rating curves can be difficult due to its remote character.

Rainfall-runoff models representing the hydrological cycle and its processes have been widely used to fill the gaps either in streamflow time series data or for areas where no observations are available. To complement measured streamflow for the application of estimating freshwater influxes to the marine environment, we explored alternative data sources from readily available, fully operational large domain hydro-metrological models and evaluated estimated streamflow to Australia's remote Carpentaria and Tanami Timor coast. This area covers about 23 per cent of Australia and – in hydrological terms - is one of Australia's most productive areas, producing about 40 per cent of Australia's total annual streamflow to the marine environment. Yet, only 56 per cent of the area is gauged for discharge levels and streamflow, represented by 33 sites.

For our analysis we used the Australian Water Resources Assessment Landscape model (AWRA-L - www.bom.gov.au/water/landscape), which is a product of the Australian Bureau of Meteorology, and the Global Flood Awareness System (GloFAS), a product of Copernicus by the European Union (http://www.globalfloods.eu/general-information/glofas-methods/). AWRA-L currently delivers national, operational water balance estimates including rainfall, runoff, soil moisture in 3 layers, potential and actual evapotranspiration and deep drainage, on a 5 km grid, daily and up until the day before. The model uses national interpolated observations of rainfall, temperature, radiation and wind and has been evaluated against more than 700 streamflow sites across Australia.

GLoFAS is a global operational hydrological forecast and monitoring system. The purpose of GloFAS is to deliver early probabilistic warnings rather than detailed forecasts. The model produces 51 ensemble streamflow forecasts and threshold exceedance probabilities for large rivers worldwide. The system generates daily streamflow forecasts using a coupled H-TESSEL land surface scheme and the LISFLOOD model forced by ECMWF IFS meteorological forecasts. The model has been calibrated with ECMWF reruns from 1995 to 2015 as forcing, using daily streamflow data from 1287 stations worldwide.

With an emphasis on high flows, the comparison against observed streamflow from 33 sites showed good performance for AWRA-L and reasonable performance for some regions from GLOFAS. Despite the lack of routing and riverine processes, spatially accumulated daily AWRA-L runoff estimates performed better than GLoFAS for 33 Northern Australia sites. GLoFAS streamflow estimates performed reasonably well, particularly when using short-term forecast intervals, despite using forecast rainfall rather than observed rainfall for estimating runoff. Acknowledging the differences in model concepts, purposes and input data, AWRA-L is the currently recommended model for estimating streamflow from Northern Australia given its strong emphasis on the calibration to Australian hydrologic conditions. However, GloFAS can be used where both observed and estimated runoff from a well-calibrated model is not readily available, for example in other countries.

Keywords: *Hydrologic model, model comparison, model evaluation*

The effects of SILO & AWRA wind speeds on irrigation depth simulations

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Abstract: The availability of meteorological data can be sparse across Australia, particularly in regional areas, leading to the use of gridded products. Available gridded products range from measured data such as precipitation and temperature to derived variables such as the various techniques used to describe evapotranspiration (ET). The lack of automatic weather stations that provide ET, compared to numbers of rain gauges, means these gridded ET products are potentially of more value due to the large distances between users and the nearest observation.

Gridded data is currently available through the Scientific Information for Land Owners (SILO) service as well as through the Australian Water Resources Assessment Landscape (AWRA) model and datasets from the Australian Water Availability Project (AWAP). These services provide grids for many variables used in hydrology and its related fields. The AWAP and SILO products have previously been compared although they predominately focused on the differences between the rainfall variables and interpolation methods. Another key difference between the products, that relates to this paper, is that AWRA uses a climatologically derived wind speed in its ET calculations, whereas SILO assumes a speed of 2 m/s. Using a varying wind speed has been found to be an important factor in semi-arid regions when looking at crop water use, this may be particularly relevant in agricultural regions of Australia. Only the precipitation (P) and reference crop ET (ET_0) product variables will be used in this paper.

The paper describes the comparison of using the two available products as inputs to interact with the remote sensing observations obtained from Digital Earth Australia. The P and ET_0 are predominate drivers in the method. The AET is found using the methods outlined in FAO56, although the crop coefficients are derived from remote sensing observations. The simulations were performed over four sites, this includes an almond orchard, two vineyards and a cotton farm. The results show that for annual simulations, there were only small differences between the two products, although the AWRA methods produced smaller standard deviations. The 2 m/s wind speed assumed in the SILO calculation was found to be much lower than the local statistical averages at nearby gauge sites. This led to the AWRA and SILO products deviating during summer, when higher winds are causing higher ET values, which is not accounted for in the SILO dataset.

This paper aims to give an indication of the possible implementations for farmers or natural resource managers may see due to changing their systems from SILO to the technically improved AWRA product. It may also provide additional insight into how further research may be impacted by choosing one of the gridded products over the other. The current results indicate that the technical improvements implemented in AWRA are providing slight improvements in irrigation simulations. This may encourage natural resource managers to alter their methods to achieve better results for their specific scenario.

Keywords: *SILO, AWRA, irrigation, wind speed, evapotranspiration*

Anomaly kriging helps remove bias in model runoff estimates

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Abstract: The sparsity of streamflow measurements for hydrological model calibration limits the accuracy of spatial streamflow estimates. State-of-the-art approaches to improve runoff estimates in the absence of dense measurements have tended to focus on estimating model parameters in ungauged regions, through so-called parameter regionalisation methods. Several regionalization approaches have been developed, but most focused on subcontinental scale or smaller, and used methodologies, data and methods that cannot be applied at continental or global scale. Errors in input data and structural deficiencies in models, over-reliance on calibration at gauged areas and equifinality further compromise model estimation accuracy. Hydrological simulations at continental to global scale rarely use regionalized parameters, and instead tend to rely on a single set of model parameters derived from bulk calibration, expert opinion, case studies, or theoretical assumption, and sometimes poor quality datasets. As a result, spatial model runoff estimates typically exhibit spatially-correlated biases. While there have been some efforts to spatially interpolate streamflow model biases within the same river system in forecast applications, the interpolation of residuals from prior, retrospective hydrological model estimates has not yet been explored at large scales.

Our objective was to enhance the use of observations as a constraint on spatial runoff estimates by addressing spatially-correlated model biases beyond initial model parameter estimation. Specifically, we assessed the potential to reduce systematic errors by spatially interpolating residuals between prior grid-based streamflow estimates for Australia at 0.05° x 0.05° from the Bureau of Meteorology's operational Australian Water Resources Assessment model (AWRA) and streamflow gauging records for 780 undisturbed natural headwater catchments. We analysed the characteristics of spatial auto-correlation in these residuals and trialled a simple but efficient kriging approach.

We conclude that residual interpolation can indeed be used successfully to remove a considerable amount of systematic bias in the spatial hydrological model predictions. Subsequent research will test whether further reductions at shorter time scales can be achieved through a temporally-hierarchical bias correction scheme.

Keywords: *Streamflow, bias, spatial interpolation, hydrological modelling, water resources*

Improvements to the Australian Water Resource Assessment Landscape Model from new remotely sensed data, calibration targets and process descriptions

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Abstract: The Australian Water Resources Assessment Landscape model, AWRA-L, is a nationally consistent 0.05° (~5km) gridded soil and groundwater balance model which provides estimates of landscape water yield, evapotranspiration, soil moisture, and groundwater recharge across Australia. The model outputs are mostly used for retrospective water resource assessment, national water account and soil moisture monitoring and are available through the Australian Landscape Water Balance Website (www.bom.gov.au/water/landscape) for the period 1911 until yesterday.

The AWRA-L model aims to optimally simulate hydrology nationally and across the water balance and calibration criteria and benchmarking is designed to evaluate this. Benchmarking of the current version, AWRA-L v6, indicated poor performance in the top layer (0 – 10 cm) soil moisture and potential improvements to be made in evapotranspiration. Newly available data was also hypothesised to give model improvements. As such, a series of experiments to test potential improvements was designed. The potential improvements were: 1) improving the drainage equation for top soil-moisture, 2) checking alternative objective functions, 3) incorporation of new observations including Advanced SCATterometer (ASCAT) soil moisture, 4) 8-day CSIRO MODIS reflectance based scaling evapotranspiration (CMRSET) in calibration process, 5) incorporating vegetation-related observation from MODIS (i.e. vegetation fraction and Albedo), and 6) improving the vapour pressure equations.

To find the overall best modelling system setting, it is not enough to unilaterally assess the change in the system performance by changing the components one by one. The reason is the fact that the components interactively affect each other and should be assessed with a holistic approach. Moreover, it is difficult to define a single measure that shows the model overall performance as the model produce a range of flux and state variables, all of which are valuable to parts of our user community. Therefore, a model setting can improve some of the variables while degrading others. In this study, we observed strong trade-offs between the accuracy of different variables e.g. top and profile soil moisture. The results of these experiments led to a number of new model setting with performance improved (Figure 1).

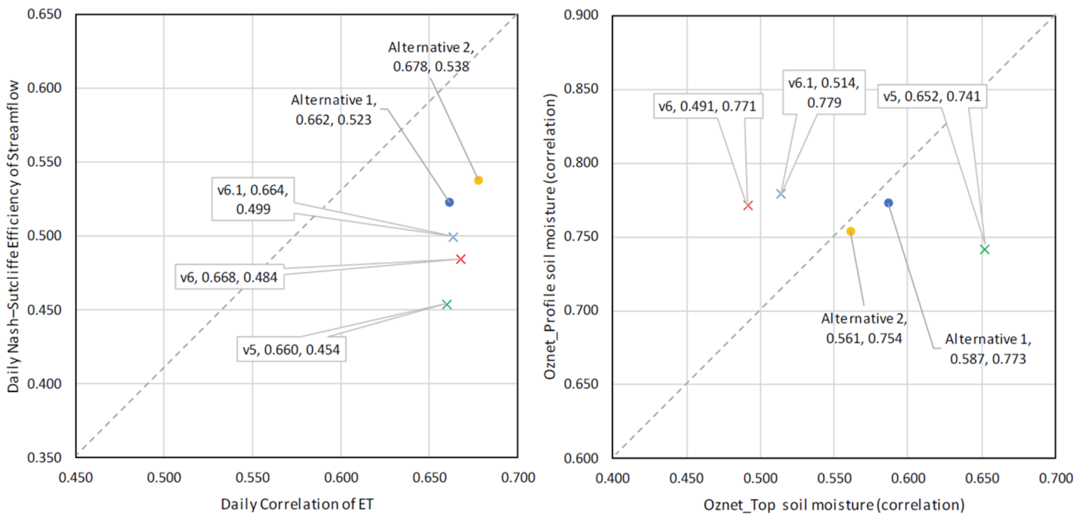

Figure 1. AWRA-L Performance improvement in estimation accuracy of top and profile soil moisture in OZnet sites, ET in OZflux sites, and streamflow of validation catchments. Alternative 1 and 2 were made using updating the model drainage and vapour pressure equations, soil moisture, evapotranspiration observations.

Keywords: *AWRA-L, hydrological modeling, calibration*

Remotely sensed data for calibrating hydrologic models

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Abstract: Decades of experience has shown that streamflow data are essential to properly calibrate a hydrologic model. This means that hydrologic events are harder to predict in ungauged basins due to lack of the data. To overcome this deficiency, efforts such as regionalization have been used to estimate streamflow in ungauged basins. Another suggested approach is to use remotely sensed data to fill the absence of streamflow. One remotely sensed variable, the Measurement-Calibration (MC) ratio data has received increasing attention because it is well correlated with streamflow. The MC ratio is a brightness temperature of wet measurement (M) divided by dry calibration (C), the signal received from passive microwave radiometers. Since the MC ratio can be a powerful alternative to streamflow in ungauged basins, multiple studies have been aimed at enhancing the MC ratio's quality or to developing methods for usage of the MC ratio in hydrologic applications.

This research seeks to calibrate a hydrologic model with MC ratio data. The main objective of the research is to quantify the performance of calibrated flow when streamflow observations are not available. The widely used rainfall-runoff model GR4J is selected as the model of interest because of its parsimonious form and efficiency. It is calibrated using Markov Chain Monte Carlo (MCMC) sampling, which allows uncertainty analysis of the calibrated results. The method uses an enhanced estimate of MC ratio based on the derivation of the topographic wetness index (TWI) using a 500-m Digital Elevation Model (DEM). The hydrologic model is calibrated in two ways; first using the observed streamflow, second using the MC ratio. Each case is compared and a detailed analysis is conducted in three representative catchments. In particular, the Reliability (the percentage of observed data located in the 90% confidence interval) is calculated to show the accuracy of each case, and the Sharpness (the width of the confidence interval) is calculated to deduce the uncertainty of each case.

Our results show that the MC ratio is an ideal surrogate for streamflow data in catchments without on-the-ground observations, as the outputs of MC ratio show high reliability and follow the dynamics of in-situ streamflow. However, use of the MC ratio increases the predictive uncertainty of the simulations. Understanding and quantifying this induced uncertainty will be dealt with in following research.

Keywords: *Satellite data, remotely sensed data, MC ratio, ungauged basin, MCMC sampling*

EXTENDED ABSTRACT ONLY

Comparison of three approaches to groundwater recharge estimation

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Abstract: The large majority of groundwater recharge to the Great Artesian Basin in Australia occurs over a small fraction of the basin area, in the recharge zones. One recharge zone is the Main Range Volcanics outcrop on the western flank of the Great Dividing Range in southwest Queensland. One of the major uncertainties in assessing sustainable extractions from the Great Artesian Basin, and when assessing recovery times following the short-lived (but large) groundwater extractions of the coal seam gas industry, is recharge.

Although recharge cannot be directly measured, various estimation approaches exist. All involve significant assumptions and uncertainty, and unless some consensus can be reached over what is the most suitable approach in any location, ideally multiple methods would be employed. Differences in results can illustrate uncertainty and may also indicate errors and limitations in one or more of the approaches. Additionally, such differences can also arise from different physical representations of recharge processes inherent to each method.

Three methods of recharge estimation are applied here: chloride mass balance, surface water balance modelling, and stream flow recession analysis. The chloride mass balance is based on approximately 1200 measurements of groundwater chloride from the aquifer vertically below the outcrop area. Its primary assumptions relate to mixing of the chloride in the groundwater and losses of chloride due to surface runoff leaving the basin. Kriging is employed in conjunction with chloride mass balance to spatially estimate recharge. The surface water balance modelling employs the Australian Water Resources Assessment Landscape (AWRA-L) model of the Bureau of Meteorology. This simulates the separation of rainfall into surface runoff, evaporation, and vertical drainage at 6 m below ground surface. The latter, known as deep drainage, is assumed equal to groundwater recharge. Alternative approaches to AWRA-L parameter calibration are tested over seven catchments, each dominated by the Main Range Volcanics outcrops. The stream flow recession analysis attempts to determine the relationship between (baseflow-generating) groundwater storage and stream flow. The stream flow time-series is then used to quantify increases in storage following rainfall events, and this increase in groundwater storage is considered to be recharge.

The spatially interpolated chloride mass balance method gives long-term recharge estimates of approximately 9 mm/year (around 1.4% of long-term rainfall). The maximum point value was 185 mm/year and the minimum was 0.3 mm/year. These values would be lower if chloride losses (e.g. from runoff) had been accounted for. The AWRA-L model run over the period 2000-2018 using calibration to each catchment's stream flow gave an outcrop-average estimate of 51 mm/year (8% of rainfall). This value varied from 11 mm/year to 112 mm/year over the seven modelled catchments, and the outcrop-average varied from 10 mm/year to 51 mm/year depending on which calibration approach was used. The stream flow recession analysis gave a long-term average recharge value of 6.2 mm/year (1.1% of rainfall). Over the 10 included stream flow gauges, the results varied from 0.2 to 27 mm/year. The recession analysis method produced a long-term time-series of event recharge, which illustrated the strong influence of large events and non-linearity between recharge and rainfall. The nature of the recession analysis method means it is expected to slightly underestimate recharge.

These results are also compared to previous analyses of recharge for the Main Range Volcanics, which gave values of long-term recharge between 1.9 to 2.3% of rainfall. The similarities and differences between the results are discussed, as is the potential for improving the methods and merging them to extract the most valuable/credible information from each.

Keywords: *Recharge, Main Range Volcanics, Great Artesian Basin, multi-model comparisons*

EXTENDED ABSTRACT ONLY

Joint simulation of surface-groundwater dynamics at the catchment scale: a challenge

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Abstract: The world´s population will reach 9.8 billion by 2050, which combined with income growth will lead to a 50% demand increase for agricultural output. As agriculture is a water sensitive activity and climate change is expected to increase variability in rainfall and temperatures, leading to higher occurrence of droughts and floods, the use of more reliable water sources (i.e. groundwater) and the expansion of irrigation with efficiency and sustainability are key innovation requirements to meet the future agricultural demand. Yet, irrigation accounts for 70% of all water withdrawals worldwide and its expansion requires a better quantification of the impacts of its increasing groundwater (GW) usage on the water availability. This paper describes challenges faced when attempting to quantify surface-groundwater (SW-GW) interactions at the catchment to basin scale, suggests a future approach to estimate these interactions and presents preliminary correlation results between SW and GW hydrographs in Australian catchments.

Physically-based integrated hydrological models, such as HydroGeoSphere and GSFLOW, are powerful tools to analyse the impacts of different management settings, like increasing groundwater pumping and irrigation. However, given their overwhelming functionality and complexity, they require a large number of input parameters and their calibration can be very difficult. This often requires simplification of processes that can hinder the performance and reliability of their predictions. The general lack of observation data, combined with increasingly limited hydrological monitoring (Figure 1) and the complexity of the surface-groundwater processes at the catchment scale, often reduces the applicability of such models to catchment management. Conversely, conceptual rainfall-runoff models tend to oversimplify processes and underestimate the sensitivity of runoff to low frequency events and struggle to simulate scenarios where the groundwater head drop (ephemeral rivers). Consequently, it is difficult to quantify the impact of climate and groundwater pumping on the streamflow honouring both surface and groundwater hydrographs. We suggest the development of a rainfall-runoff model that contains a volumetric exchange of water between the surface and groundwater components, incorporates groundwater hydrographs to inform the slow-flow processes and improve the performance of multiyear streamflow simulations. Hierarchical modelling and likelihood functions will be used for the joint calibration of surface and groundwater hydrographs and Pareto fronts to investigate the most appropriate model structure and parameter set. Preliminary empirical analysis of SW-GW hydrographs from non-regulated catchments in Victoria, Australia, investigate the correlation between these datasets and will be used to develop and test the new rainfall-runoff model.

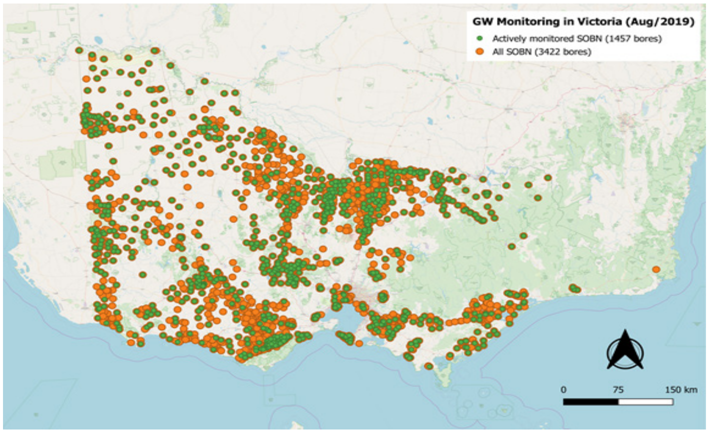

Figure 1. 1457 actively monitored state observation bores (SOBN) versus all 3422 SOBNs in Victoria as of August 2019. Data from DELWP.

This data-driven modelling approach is a promising alternative to quantify surface-groundwater interactions over time in areas with limited available monitoring data, which is of paramount importance to long-term water resource assessments and management of groundwater dependent ecosystems (GDE). Even more considering that most future economic and populational growth is expected to happen in developing countries, where the costs of environmental monitoring might be prohibiting for more and abundant observation data in the regions that would represent most of the water usage increase.

Keywords: *Surface-groundwater hydrology, data-driven modelling, groundwater dependent ecosystems*

Quantifying the contribution of multiple factors to land subsidence using artificial intelligence technology in Beijing, China

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Abstract: More than 100 cities have experienced land subsidence in the world, but few studies have been conducted to quantitatively analyze the contribution rate of various factors to land subsidence. In this study, we established the BP-ANN-MIV (Back propagation-Artificial Intelligence Neural Network- Mean impact value) model to quantify the contribution of multiple factors to land subsidence. The Chaobai River alluvial fan in Beijing, China is taken as the case study, where located the large scale well-fields and the international airport. The input parameters of the model include cumulative displacement detected by SBAS-InSAR technology, groundwater level change, the compressible layers thickness, building volume, road density data from 2014 to 2018. The results show that the average displacement rate of the Chaobai River alluvial fan ranges from −140 mm/year to +21 mm/year. And most serious land subsidence occurred in the middle of the alluvial fan area. In the study area, the contribution rates of each factor are different in different years. The contribution rates of compressible layer thickness and groundwater level change are the largest, which are 28.59% - 45.51% and 52.95% - 69.57% respectively. The influence of road density and building volume is very small, about 2%. The research is maybe helpful to managers for land subsidence prevention and control.

Keywords: *Land subsidence, BP-ANN-MIV, Contrbution, InSAR*

Quantifying the impact of climate change on groundwater

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Abstract: Groundwater, a vital fresh water resource on Earth, is influenced by changing climates and human activities. Numerous studies have sought to understand how groundwater has and may respond to climate change. In this study, we discuss the challenges and adequacies of efforts to estimate the historic impacts of climate change on groundwater, and the potential benefits to future predictions.

Various approaches and techniques have been developed to investigate the impact of climate change on groundwater. Several studies have focused on predicting future impacts using deterministic groundwater models calibrated to historic data and forced using climate change scenarios. Often their predictions of future climate change impacts require numerous assumptions about the stationarity of hydrological and land surface processes under climate change, such as vegetation dynamics and interactions between surface water and groundwater. These estimates have large uncertainties. Adding to this is the uncertainty in the Global Circulation Models (GCMs).

GCMs have been widely used to project future groundwater status in multiple countries, such as Australia, Canada, UK and USA. Differences between the results of different climate models highlight the need to be careful with our interpretation of climate model predictions. Global hydrological models provide another opportunity. However due to numerous uncertainties, including the limitations on including necessary anthropogenic and natural influences, and the differences in global water storage changes compared with the estimates from the Gravity Recovery and Climate Experiment (GRACE), their utility for estimating impacts of climate change on groundwater is questioned.

Statistical analysis of groundwater hydrographs has also attempted to investigate the historic impact of climate change. Analysing individual hydrographs potentially allows for a data-driven understanding of the regions most impacted by climate change. However, few studies have been undertaken and those that have used simple relationships between climate variability, groundwater pumping and heads and then looked for step-changes or break-points in the model residuals or hydrograph. Other drivers such as vegetation, land use change and irrigation were rarely considered.

In this study we identified several key challenges to quantifying the historic impact of climate change on groundwater level change. These include: (i) separating the influence of each contributing factor; (ii) short and often interrupted observed hydrographs; (iii) the long memory of groundwater to historical rainfall events; and (iv) the requirement for a deep understanding of the underlying hydro-climate interactions. In order to improve the precision and accuracy of the predictions under climate change, we recommend focusing on understanding and quantifying the historical response of groundwater to climate forcing. Only when we fully understand how groundwater has responded to climate change and variables in the past and present, may we make substantial improvements in predicting groundwater behaviour in the future.

Keywords: *Climate change, groundwater, modelling*

A quantitative study of the land subsidence formation mechanism on sub-center of Beijing, China

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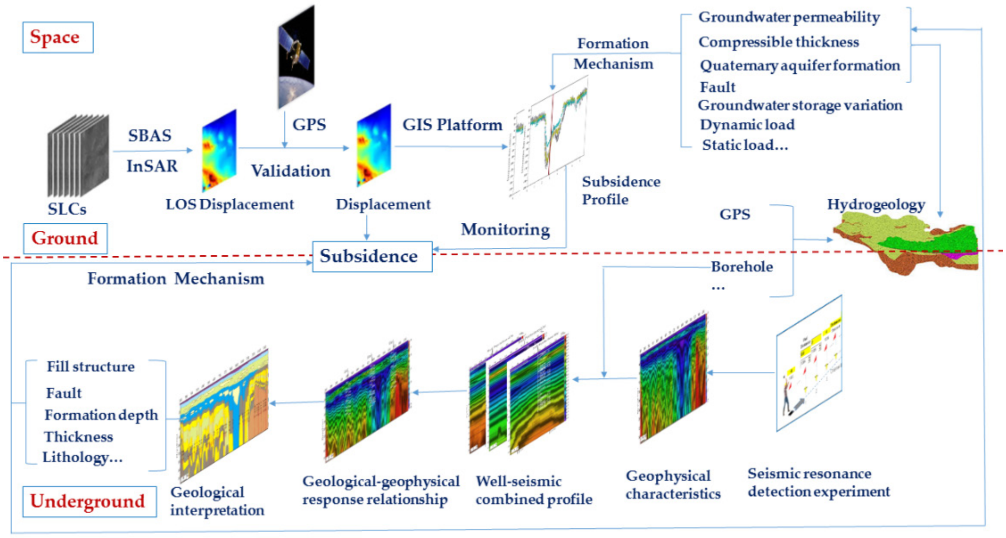
Abstract: Since the 1970s, land subsidence has been developing rapidly on the Beijing Plain, and the systematic study of the evolutionary mechanism of this subsidence is of great significance to the sustainable development of the regional economy. In this study, an integration model of "space-underground" in typical areas of Beijing was established, and formation mechanism of land subsidence was quantitatively analyzed. First, this research used 43 descending Sentinel-1 A/B data covering the Beijing Plain from 2014 to 2018 and adopted SBAS-InSAR technology to monitor the displacements of the Beijing Plain and validate the deformation results with GPS data. Second, in the urban and rural differential settlement areas, we combined seismic resonance experiments and the hydrogeological conditions to quantitatively reveal the formation mechanism of differential subsidence in the sub-center of Beijing. The results shows that: 1. From 2014-2018, the average deformation rate of the Beijing Plain ranges from −136.78 mm/year to +13.34 mm/year and the sub-center area ranges from -101.47 mm/year to +13.34 mm/year, with an average settlement rate of -12.99 mm/year.2.The natural fault zone controls the land subsidence funnel edge of study area with respect to expansion in the southeast direction. 3. From 2014 to 2018, the land subsidence rate showed obvious segmentation at some faults .4. We analysis the land subsidence significantly differ between the urban area and the rural area combines with hydrogeological conditions. This research is of great significance to the prevention and mitigation of land subsidence and provides scientific basis for urban planning.



Flowchart of data processing

Keywords: *Land subsidence, InSAR, Geophysical prospecting, Space-underground model, Formation mechanism*

Groundwater modelling-A tool for sustainable aquifer management under changing climate

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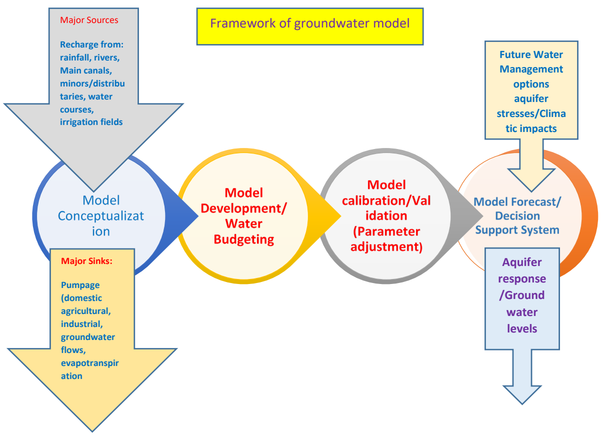
Abstract: Groundwater is generally considered as an invisible and silent component of hydrological cycle which is being pumped globally at an estimated rate of 750-800 billion M^3/year and has become the mainstay of irrigated agriculture which underpins the food security. The aquifer in Pakistan is a part of transboundary Indo-Gangetic aquifer which comprises almost 25% of global groundwater withdrawals and sustains agricultural productivity in Pakistan, India, Nepal and Bangladesh. Pakistan has become one of the largest groundwater-user countries - 4th largest after India, China and USA - where groundwater caters for 50% irrigation water, more than 90% drinking water and almost 100% industrial water requirements. The lack of holistic regulatory/policy framework, rapidly increasing population, industrialization, poor water productivity, week institutional framework are the major drivers for over-depletion of groundwater in the Pakistan. Management of groundwater has not been paid the appropriate attention resulting in over-exploitation of aquifer in freshwater areas, degradation of quality and increase in the cost of pumping. Pakistan is an agricultural country having an irrigation-based economy which puts it as the 8th largest food producing country where irrigated agriculture contributes more than 90% of food production. Water resources of Pakistan are under serious threats of global climatic changes. Changing patterns of rainfall, floods and droughts have led to uncertainties and deficiency in surface water flow putting tremendous pressure of groundwater reserves. Pakistan lies in the heat surplus zone on the globe and is suffering adversely from the impacts of global warming. Unprecedented floods and droughts have put the water resources of the country under stress and Pakistan has become 10th most climate-vulnerable country although it is 135th in GHG emissions.



The present paper encapsulates the findings of a project funded by the Asian Development Bank for groundwater monitoring, modelling and management in an irrigated canal commanded area of Punjab province of Pakistan where groundwater is contributing about more than 50% for crop water requirements. Groundwater system in the study area has become complex due to multiple users, undefined hydrogeology boundaries, alluvial nature of aquifer, spatial and temporal variability of surface water (river flow and rainfall). Punjab Irrigation Department (PID) has installed a network of about 800 piezometers to monitor the groundwater levels in the study area. A three-dimensional transient numerical groundwater model- MODFLOW- for Lower Bari Doab Canal (LBDC) command area has been developed and calibrated to help understand the overall groundwater potential and conditions for different hydrological and water management specific scenarios to cater for the increasing and varying water demands in future. The calibrated groundwater model was used to perform long-term simulations for predicting future groundwater conditions in the study area to determine spatial and temporal changes in groundwater levels caused by the implementation of different water resources management strategies under changing climatic conditions. Model results indicated that for next 18 years, we need to reduce the groundwater pumpage rate as well to enhance the surface water supply for aquifer sustainability. This was a unique study in Pakistan's context where groundwater models has helped in decision making.

Keywords: *Groundwater, climatic changes, livelihood, Punjab, Pakistan*

A data-driven model to simulate groundwater levels – Application to an urban agglomeration in India

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Abstract: Groundwater is one of India's largest sources of water supply. According to the world bank report (2012), 85% of drinking water needs in India are met from groundwater sources. Due to intermittent and variable surface water supplies, urban areas are heavily dependent on groundwater. The rapid growth of urbanization impacts groundwater resources in the form of overexploitation, reduction of recharge zones, and deterioration of groundwater quality. Hence, it is important to quantify the processes of recharge and groundwater levels to implement sustainable water management practices. In this study, we considered the case of Hyderabad, one of the fastest growing mega cities in India, having heterogeneous sub-surface conditions. A data-driven model was developed to estimate groundwater levels at monthly time steps using precipitation, lateral flow, and pumping rate. The model framework involves a two-step process: i) simulation and optimization of the model, and ii) uncertainty analysis to quantify the variability of the model results due the input parameters.

The model is based on the water balance approach to simulate recharge (as a function of rainfall) and groundwater levels at a monthly time scale. Simulation of the model is performed using non-dominated sorting genetic algorithm (NSGA-II) by considering three scenarios: i) constant recharge factor for each month (case-1), ii) monsoon driven seasonal recharge factor (case-2), and iii) climate driven seasonal recharge factor (case-3). The calibration of the model is carried out using the data from years 2004-2007 and validation is performed for the year 2008. Groundwater recharge factor (as a fraction of rainfall) was found to be 12% (case-1), 15% and 0% (case:2 monsoon and non-monsoon), and 29%, 0%, 5% (case 3: monsoon, summer and winter). The ability of the model to capture the intra-annual dynamics of groundwater level was analysed using residual statistical indicators. Considering the best optimal solution obtained in the pareto optimal front, the model has reasonably predicted the groundwater levels for three scenarios during validation period (MAE: 1.15m,1.02m,1.04m, RMSE: 1.59m,1.39m,1.4m, NSE: 0.64,0.72,0.71). Our results show that, when considering seasonal variation in recharge factor (case-2, case-3), model performs better than using a constant recharge factor (case-1) scenario. To cope with the uncertainty in the input parameters of the model, generalised likelihood uncertainty estimation (GLUE) was used. Results of this study revealed that specific yield and pumping rate are more sensitive in comparison to the recharge factor.

Keywords: *Recharge, data-driven model, water balance, groundwater level, multi-objective optimization and uncertainty analysis*

Joint estimation of gross recharge, groundwater usage and hydraulic properties within *HydroSight*

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Abstract: Groundwater management decisions are often founded upon estimates of aquifer hydraulic properties, recharge and the rate of groundwater usage. Too often hydraulic properties are unavailable, recharge estimates are very uncertain, and usage is unmetered or infrequently metered over only recent years or estimated using numerical groundwater models de-coupled from the drivers of drawdown. This paper presents an extension of the HydroSight groundwater time-series package to allow the joint estimation of gross recharge, transmissivity, storativity and daily usage at multiple production wells.

A genetic evolution calibration approach for estimating model parameters was extended to also estimate time-series of usage that honoured metered volumes at each production bore and produced (i) the best fit with the observed hydrograph and (ii) plausible estimates of actual evapotranspiration; and hence recharge. Application to the 30 observation bores within the Warrion groundwater management area (Australia), produced a coefficient of efficiency of ≥0.80 at 22 bores and ≥0.90 at 12 bores. The aquifer transmissivity (Fig. 1) and storativity were reliably estimated, and were consistent with independent estimates, while mean gross recharge may have been slightly overestimated. Overall, the approach allows estimates of fundamental aquifer properties from commonly available data. For further details see Peterson and Fulton (2019).

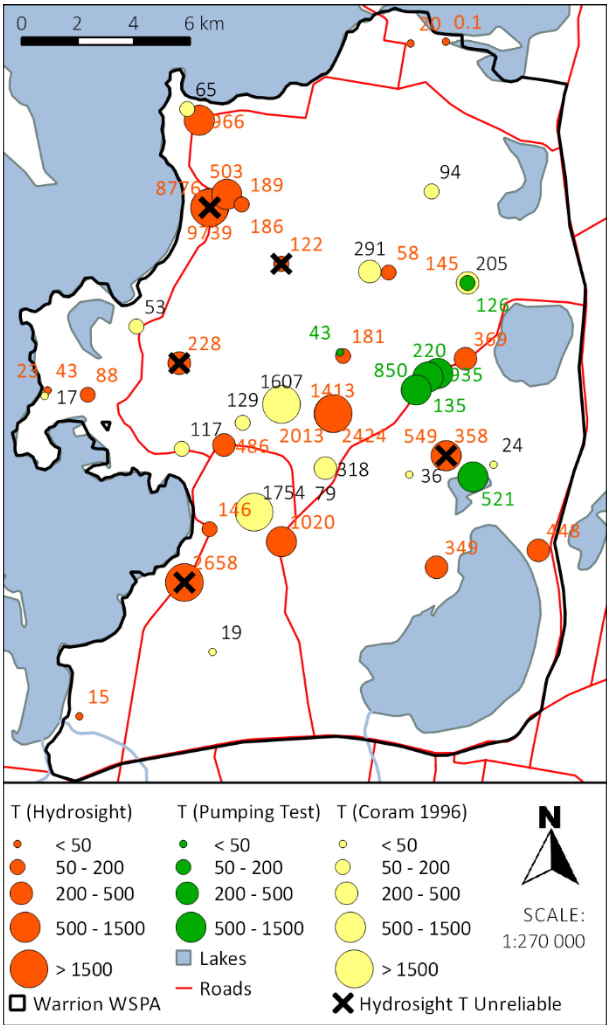

Figure 1. Comparison of HydroSight estimations of transmissivity against independent estimates.

Keywords: *Groundwater, time-series analysis, aquifer properties, recharge, HydroSight*

Quantifying transient lateral river-aquifer exchanges through the joint simulation of groundwater flow and heat transport

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Abstract: Heat as a tracer has been widely used for assessing river-aquifer exchanges through riverbeds. In many situations, rivers can become deeply incised into the adjacent aquifers. Lateral river-aquifer exchanges through riverbanks can become more important compared to vertical exchanges via riverbeds in such situations. Few studies have investigated lateral river-aquifer exchanges and the ability of temperature data to constrain modelled exchanges. The presented study is based on a section of the Meuse River in Belgium, a river predominantly gaining in the studied area and becoming intermittently losing in the winter time. The main objective of this study was to perform a robust assessment of the ability of heat as a tracer to quantify transient lateral river-aquifer exchanges by simulating groundwater flow and heat transport simultaneously.

A transect model was established to simulate groundwater flow and heat transport using HydroGeoSphere. The model was meant to be calibrated with both hydraulic head and groundwater temperature data. However, the attempt to calibrate the model with the groundwater temperature was unsuccessful. The heat transport simulation shows that river temperature can only affect groundwater temperature up to 9 m into the aquifer, whereas our temperature observations were made more than 100 m away from the river. Despite this issue, the calibrated model can be treated as a synthetic base case for investigating optimal well location for collecting groundwater temperature data.

In the following synthetic modelling exercise, the Monte Carlo simulation approach was adopted to simulate groundwater temperature by sampling parameters in their respective uncertainty ranges. Those models that have equally reasonable fitting to head and/or temperature data at one or multiple specific locations can inform river-aquifer exchange flux uncertainty, the degree of which will then indicate optimal well location for data collection. The Monte Carlo simulation shows that temperature data for distances between 4 and 9 m from the river can reduce the uncertainty of river-aquifer exchanges for conditions similar to that of our transect model. The ability of temperature data to reduce the river-aquifer exchange uncertainty improves with distance from the river. This finding may be counterintuitive but reasonable because the temperature time series are more fluctuative closer to the river and can be easily fit with more models which result in a wider range of river-aquifer exchange. In this specific work, the optimal distance is 8 m from the river where the groundwater temperature is no longer strongly affected by the river temperature. The synthetic modelling also indicates that temperature data alone cannot constrain modelled transient river-aquifer exchanges better than commonly used hydraulic head data. However, when combined with the head data, the temperature data can significantly reduce the uncertainty of river-aquifer lateral exchanges under gaining conditions such as our study site (Figure 1).

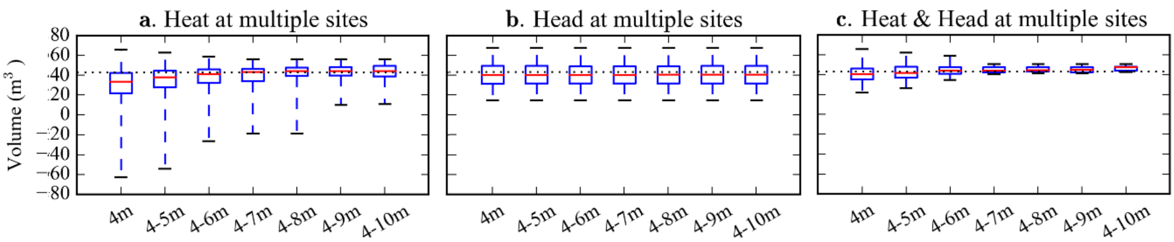

Figure 1. Net river-aquifer exchange volume statistics for using hydraulic head and temperature time series to calibrate the model in different manners: (a) the temperature time series were used only at specific ranges of well locations (e.g., 4-5 m indicates well locations at both 4 and 5 m, and 4-6 m indicates well locations at 4, 5 and 6 m); (b) the head time series were used only; (c) both the temperature and the head were used together. The dotted lines show the net exchange volume for the base case model.

Keywords: *River-aquifer interactions, heat transport, heat as a tracer*

Using a multiple lines of evidence approach to streamflow calibration in river system modelling

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Abstract: The Department of Planning, Industry and the Environment (DPIE) of the NSW Government uses a multiple lines of evidence approach when undertaking flow calibration of river system models. This approach, supported by streamflow calibration practice guidelines, has resulted in higher quality, more consistent and transparent streamflow calibrations. Workflows have been generated to allow the automation of a suite of post processed outputs, which allow the efficient undertaking of multiple lines of validation for each stage of the streamflow calibration.

This approach first required the creation of surface water modelling guidelines and quality assurance processes. These guidelines and associated practice notes outline the procedures and multiple lines of evidence required during the calibration process. This is an integral part of the calibration process especially when using automated methods as it sets a framework of appropriate quality checks and assurance. Streamflow calibration is an iterative process that can be simplified into three main stages (Figure 1), which include data review, calibration and validation. Multiple lines of evidence are correlated to each stage of the process to justify the quality of the results.

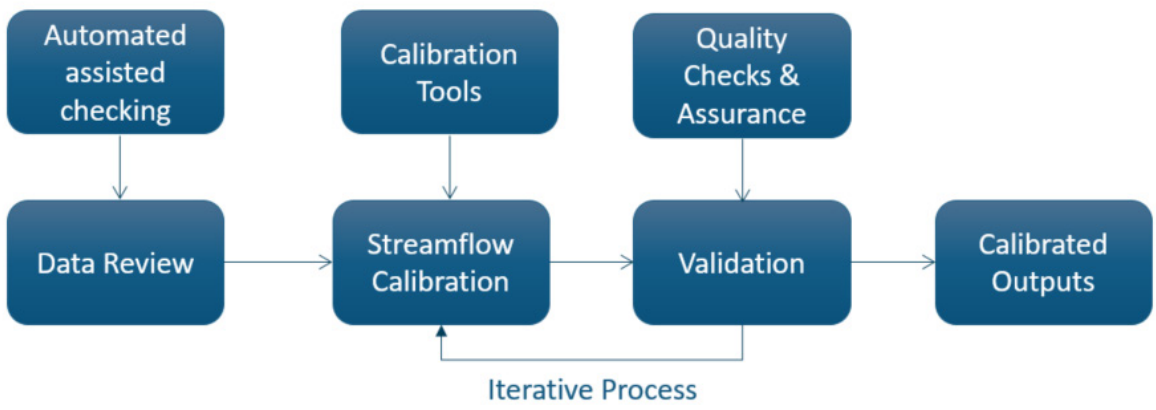

Figure 1. Simplified Schematic of Streamflow Calibration

The data used in the calibration is reviewed efficiently using visualisation tools and post processed statistics. The reviewed data is then used in calibration using developed and tested tools to enable an effective and consistent approach. Calibrated outputs undergo quality assurance and validation using a multiple lines of evidence approach; allowing both a focused iterative process and better outcomes. Techniques used in the multiple lines of evidence approach include: a suite of statistical metrics, dashboard summaries, cross validation spatial plots, validation of calibration to a suite of different periods, Budyko curve plots, flow duration curves, shortfall analysis and double mass curves. Where relevant, other lines of evidence have included outputs from other models such as hydraulic modelling and river operator spreadsheets.

The paper presents the development and application of the approach through a series of examples used in building NSW's river system models in eWater Source Software platform.

Keywords: *Streamflow calibration, river system modelling, automation, visualisation tools, practice notes*

INVITED PAPER

EXTENDED ABSTRACT ONLY

Evaluating the suitability of generated climate data for water security assessments

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Abstract: An understanding of likely climate variability and change is critical for the development of sustainable water resources management plans. This is particularly true for Australia, as annual streamflow variability in Australia is the highest of the inhabited continents (equalled only by South Africa), and this has direct implications for water resources management. Dams in Australia, for example, need to be larger than elsewhere in the world to provide the same reliability of supply. By introducing added uncertainty, climate change has affected, and will continue to affect, the volume, location and timing of water availability.

In New South Wales (NSW), historical records of rainfall and evaporation (or temperature) are available from the late 1800s onwards. This data provides information on recent historical climate variability, but, ideally, water resources planning should also consider long-term historical climate patterns and future climate change. Palaeoclimate methods infer information about climate conditions prior to the instrumental record using indirect data sources, such as evidence preserved within rocks, sediments, ice, tree rings, and other sources. This information can be combined with historical observations to create long 'stochastic' time series of climate variables that can be used to supplement the historical record. Local climate change estimates are typically obtained by downscaling the results of general circulation models (GCMs).

The sequences of rainfall and evaporation generated by stochastic palaeoclimate methods and climate change models are subject to biases and uncertainty that vary depending on spatial location and temporal frequency (e.g., daily verses seasonal or annual climate patterns). This paper presents an approach for evaluating the suitability of generated climate data for use in water security assessments, focusing on drought resilience. The key question is, what types of changes in rainfall and evaporation have a significant impact on catchment runoff yields?

In the first part of this paper, generated climate data is compared with historical observations for northern NSW river basins, and results regarding the quality of the data for differing geographic regions and temporal frequencies are presented. In the second part, existing, calibrated rainfall-runoff models are simulated using the generated and historical climate data. Analysis of the relationships between climate variations and streamflow provides interesting insights regarding the importance of these factors to streamflow generation. Finally, we discuss implications of the results for water supply security in NSW.

Keywords: *Climate variability, rainfall-runoff generation, water resources management, water security*

Development of Practice Notes to support consistent, transparent and efficient implementation of eWater Source across the Murray Darling Basin

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Abstract: Hydrological models are used to underpin different policy and management decisions in our regulated river systems. Historically, in Australia, various water management agencies have used different modelling platforms and different approaches to develop the models that underpin water resource planning. Since the mid-2000's agencies have been working collaboratively to build a standard modelling platform (eWater Source) to support water resource planning in Australia. This Source modelling framework is now being implemented across the Murray Darling Basin (MDB), as well as in various other jurisdictions in Australia and internationally. As part of the implementation of Source in the MDB, the Murray Darling Basin Authority (MDBA) and key state organisations have been working to develop a set of practice notes to improve the consistency, transparency and efficiency of model development across the Basin. These practice notes aim to provide high-level principles that should be followed during model development and calibration and draw on the experience of MDBA and State modellers to guide their development. This paper details the progress to date in the development of the hydrological modelling practice notes and the collaborative approach used in their development.

In 2015, MDBA conceived the idea of developing a set of Practice Notes to improve the consistent, transparent and efficient implementation of Source across the MDB. Improving the consistency of model development should make models easier for other modellers to understand, hence improving the transparency in development and use of the models. This should improve the useability of the model by those not involved in the initial development. All these will lead to efficient implementation of Source in the development and use of the models. Initially the development of the Practice Notes focused on the need to make the way for storing data and naming conventions consistent across models. The practice notes initially focused on conventions, such as how to name nodes and links, and folder structures for storing functions and input data.

The development of practice notes for model calibration is more difficult as modellers often have unique approaches to calibration. In the development of the model calibration practice notes, senior modellers from different jurisdictions and MDBA worked together to understand current practices and document high-level principles that are recommended to be followed during model development. Adopting a collaborative approach to the development of the practice notes has provided an invaluable opportunity for modellers from different jurisdictions and MDBA to discuss and better understand why a particular method has been adopted within different jurisdictions. This process has seen the publication of practice notes on, Modelling the reach water balance, Modelling Urban Demands, Estimation of Unmetred Irrigation Diversions, and, Calibration of Crop Water Models.

The development of the practice notes has provided a successful forum for jurisdictions and MDBA to work together with the collaborative process supporting consistent, transparent and efficient implementation of Source across the MDB. This project has seen the publication of 13 practice notes on MDBA website (https://www.mdba.gov.au/publications/mdba-reports/hydrologic-modelling-practice-notes), and it is expected this number will increase in the coming years as this collaborative approach continues.

Keywords: *Hydrological modelling, eWater Source, river systems*

Disaggregating water usage data in the complex river system using a constraints-based framework

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Abstract: Hydrological modelling needs input data to simulate real-world scenarios, and the quality of this data is central to the quality of the calibrated streamflow or water demand models. In many river systems in New South Wales (NSW), Australia, a common challenge is the time step of the reported water usage data. In NSW, the Water Accounting System (WAS) database records both surface water orders and extractions from regulated river systems. The WAS database contains data from 2004 to present, but the water usage recorded in the database cannot be directly used in a daily time step model as it is recorded as accumulated values between meter readings. River system modellers use a variety of manual techniques to identify and manipulate the aggregated usage records to create a daily time series, however, the process is tedious and error-prone. A more efficient, repeatable and transparent method is to build an automatic system as a part of a modelling workflow for disaggregating the data to the daily time series required for both flow and demand calibration.

To aid in the development of new river system models, we have built a constraints-based framework with general applicability to disaggregate the surface water usage data obtained from the WAS database for a complex regulated usage debit river system in NSW. The disaggregation framework facilitates the incorporation of information about licence types and periods of access to different entitlement types (illustrated in Figure 1).

In the WAS database, water usage is reported at irregular intervals, and can be obtained for the different extraction sites. These sites represent a physical location associated with pump capacities for approved works. A given extraction site may have multiple water licences associated with it. The challenge, therefore, is to develop a daily extractive water usage time series for all river sections for each different extractive entitlement type. The disaggregation method has number of key features to filter the data, disaggregate with pump capacity and access periods constraints, water balance quality assurance, and consolidating entitlements to individual extraction sites.

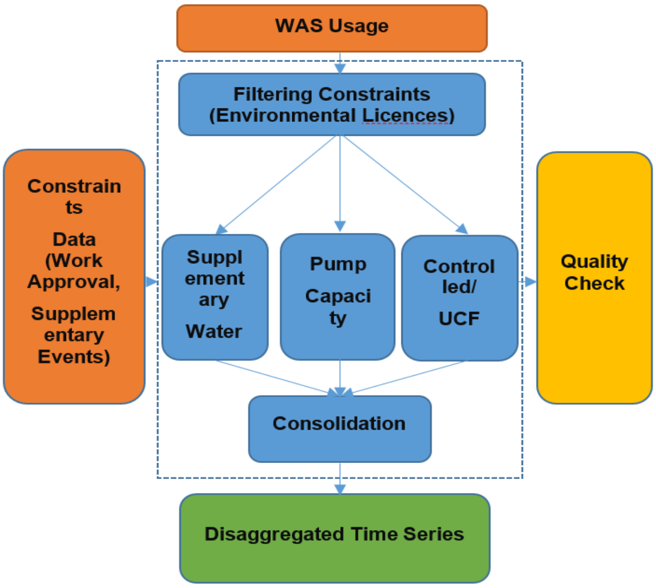

Figure 1. The proposed constraints-based framework for disaggregating water usage data

The framework has been implemented using R scripts to systematically incorporate the constraints. This constraints-based framework allows the irregular recorded data from WAS to be disaggregated in a consistent way into the daily time step form required for model calibration. The outputs include daily total diversions by entitlement types.

Keywords: *NSW regulated rivers, disaggregation, water usage, data quality, irregular interval*

Considerations in developing an optimisation modelling tool to support annual operation planning of Melbourne Water Supply System

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Abstract: Melbourne's water supply system is a complex interconnected system of 10 major storage reservoirs, over 40 service reservoirs and hundreds of kilometres of tunnels and pipelines. The system is operated based on many considerations including the volumes to be sourced from various sources to maintain water security, environmental water requirements, the distribution of storage (both spatial and seasonal) within the water supply system, minimising the risk of uncontrolled releases from water harvesting sites, water quality, scheduled outages of system assets and operating costs. Every year, Melbourne Water (MW) prepares an annual operating plan (AOP) for the bulk water entitlement holders of the Melbourne supply system. The plan details the anticipated operation for the water supply system under several streamflow scenarios. The AOP outlines the planned system operations for the 12 months ahead, and identifies for each month the expected volumes of water to be sourced, stored, moved from one location to another or released to waterways. The preparation of this forecast is a complex task, as the decisions on system operations need to be made under many considerations as outlined earlier. Melbourne Water had previously developed and used an optimisation modelling tool, OPTIMISIR, to assist in identifying the optimal annual operating plan. The tool comprised a standalone optimisation modelling program and a spreadsheet-based user interface. The weaknesses of OPTIMISIR in regards to useability, flexibility and extensibility brought about the need to develop a replacement tool addressing these issues.

Through an applied research project undertaken for MW by Monash University, a new modelling tool (Flexible Operations Water Planner - FLOWPlan) was developed addressing the above issues and needs. FLOWPlan is based on the MiniZinc modelling system developed at Monash (https://www.minizinc.org), integrated into a custom, web-based user interface. This enables interactive, human-in-the-loop optimisation: (1) A user modifies scenarios through the web interface, (2) MiniZinc combines the input with an underlying optimisation model and translates it into input for a Mixed Integer Programming (MIP) solver, (3) the MIP solver produces an optimal solution, (4) the system updates the user interface, and the user can continue again with step (1).

FLOWPlan provides the flexibility for users to specify various streamflow and demand scenarios, operating requirements, system storage conditions and the aims of the optimisation expressed as an objective function**.** It provides the functionality to assist in preparing the AOP as well as monthly review and reporting against the AOP. The key features of the tool include easy accessibility over the web, interactivity, ease of use and the flexibility of further expansion. FLOWPlan enables generating an optimum unconstrained operating solution (free of operating preferences) as an "ideal" outcome which assists in understanding the implications of operating preferences that result in constrained solutions. A key need in developing the tool was its useability by personnel without a modelling background. This required focusing on several considerations in addition to the analytical aspects that usually receive more attention in a modelling system development project. These include: designing the user interface to replicate the input and output formats of the currently used spreadsheet tool, masking the intricacies of optimisation model constructs and working closely with the users to understand their requirements (which evolved as their understanding increased) and demonstrating the value of the tool. Some of the unrealistic solutions, quite correctly generated by the tool due to its assumed "perfect foresight", needed to be worked through with the users to explain why they have been identified and how to configure the input parameters to avoid such unrealistic solutions. As the tool was being improved, additional requirements were identified and incorporated. However the nature of mathematical optimisation meant that a trade-off between the level of detail and the effectiveness was needed. The presentation will detail the considerations and trade-offs in developing the tool and demonstrate how a modelling tool which assumes perfect foresight can be used in planning operations under uncertain future conditions.

Keywords: *Water Resource planning, optimisation, FLOWPlan*

Application of natural hydrological cues for enhanced delivery of environmental water: proof of concept study

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Abstract: Over 2,000GL of water has been recovered for environment in the Murray-Darling Basin under the Basin Plan. It is prudent that the recovered water is used in a best possible way to deliver optimal environmental outcomes. Held water entitlements are unlikely to be large enough to deliver a range of fresh and overbank flows solely from storages. However this can be achievable with enhanced delivery of environmental water capitalising on opportunities for topping up unregulated flow events best using the available channel capacity. To facilitate this requires more efficient active management of environmental water portfolios by more closely linking environmental water management and river operations. With this idea, a proof of concept, called natural hydrological cues (hydro cues) method of environmental water delivery, was developed. Conceptually, the approach attempts to mimic natural flow regime while delivering environmental water with respect to variability and seasonality such that some of the freshes, inner-floodplain flows, connectivity and end of system flows, intercepted and stored by dams, are reinstated. This method aims to release environmental water in harmony with natural hydrological cues in order to restore some elements of natural flows across tributaries, which is likely to create more conducive environmental conditions for biological responses to trigger and sustain. The method is generic and it uses without development condition flow as shown in Figure 1 to trigger environmental water release from storage. This type of managed watering would mainly occur in moderate to wet years, but could occur in any year if the hydrological conditions exist.

The method was initially applied to model hydrology changes due to constraints relaxation in the southern connected basin in 2016, then to the SDL adjustment mechanisms in 2017. The study has shown with more efficient delivery of environmental flow, it would be possible to achieve: (1) improved environmental outcomes as indicated by the increased frequency of flow indicators and ecological scores; (2) reduced risk of uncontrolled flooding in the mid-Murray due to creation of more airspace in the storage from the use of environmental water earlier in the season; (3) better coordination and alignment of flows, resulting improved high flow events in the lower Murray; and (4) additional benefits with constraints relaxation through increased opportunities for more managed releases and effective utilisation of available channel capacity for more flexible river operation.

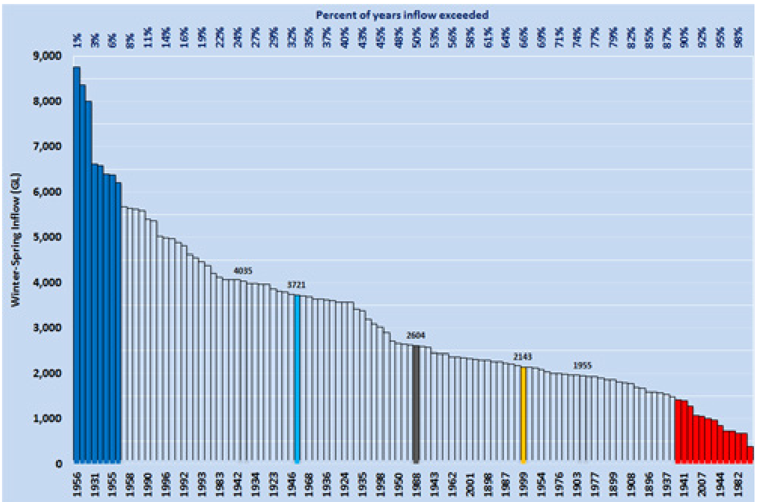

Figure 1. Natural hydrological cues conceptual framework

This is a work in progress to devise a hydro cues delivery strategy under Basin plan implementation, which will provide guidance to environmental water holders and river operators to: (1) more accurately align the release of held environmental water with unregulated flows to shape the peak and/or duration of a flow event, coinciding with natural climate signals; (2) make efficient use of available channel capacity; and (3) coordinate environmental water releases across tributaries of the southern basin to maximise downstream and system-wide connectivity outcomes.

Keywords: *Natural hydrological cues, enhanced environmental water delivery, southern connected basin*

Multiple lines of evidence for robust demand configuration in a NSW river system model: a case study

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Abstract: Sustainable and integrated water management within New South Wales (NSW) has been governed by the various water reforms and agendas. River system models have been pivotal in aiding planners, and policy makers in these water reforms. The Department of Planning, Industry and Environment (DPIE) endeavours to build models that are robust and fit for purpose to inform the decision making process.

Where possible, a multiple lines of evidence approach is used during model development to ensure that model components are robust. This multiple lines of evidence approach has been adopted during the calibration of irrigation demands where it is difficult to measure all available water. This paper outlines how irrigation demand models have been calibrated in the northern inland rivers of NSW and discusses the challenges remaining to improve these calibrations.

Irrigated agriculture demand makes up a significant proportion of water use in NSW inland valleys. Crop models are used to represent water demands from agriculture. Irrigation demand models have previously been developed to achieve a good calibration to metered river extractions. However, it has been acknowledged that this approach does not account for unmetered water use and other non-climatic drivers such as water trades. Therefore, DPIE are adopting a revised approach to calibration of irrigation demand models to ensure that the demand model incorporate all water sources, in line with best available information about irrigation behaviour and on farm infrastructure.

Crop models simulate the area and type of crops planted based on an estimate of available water. The model then continuously simulates soil moisture through representation of the soil profile and climate, determining when water should be applied to maintain a healthy crop. Crop areas planted by the model need to vary in response to water availability. In some areas total water availability can be difficult to determine, and demand models need to be calibrated to reflect our knowledge of areas planted and typical application rates. The irrigation demand models, therefore requires a representation of all water sources. Other factors such as efficiency and on farm infrastructure are also accounted for in the crop model

With the multiple line of evidence approach, various sources of data such as farm survey, remote sensing and regional data are collated, analysed and cross checked to validate historical crop area data. Completeness and reliability of the data and methodologies are taken into consideration when comparing the different data sources. To understand the total on farm water use, two key checks are undertaken:, (1) a review of annual crop areas, and, (2) irrigation water applied per hectare on a seasonal basis. Remotely sensed data is used to review annual irrigated areas reported in the farm surveys and published data and literature are used to review application rates.

Water availability at the start of a planting season is a key factor in the estimation of the area sowed for the planting season. One of the drivers for this is the available water (account balance) on licences. In NSW, regulations allow for movement of licences and its shares on either permanent or temporary basis. Licence movement analyses within a river system provides information on behaviour and water availability especially at a farm scale. This becomes one of the non-climatic drivers that we consider when setting up the demand model. Water availability is also affected by a complex mix of management rules and these have changed over time. This needs to be accounted for during model development.

Utilising various data sources for crop configurations, ensuring sensible application rate and considerations of both climatic and non-climatic drivers are part of multiple lines of evidence approach that ensures robust irrigation demand models.

Keywords: *Integrated modelling, river system model, robust model, demand modelling*

Meeting at the confluence – an interdisciplinary approach to representing environmental water requirements

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Abstract: With environmental water being a key water user within river systems, there has been progress in representing environmental water requirements (EWRs) and passing flows in integrated water resource models such as Melbourne Water's headworks model. Incorporating environmental water adds further complexities in water resource planning and management due to being multi-disciplinary (e.g. ecologist, managers, modellers, operators), different spatial and temporal scales, uncertainties associated with representing EWRs and quantifying ecological benefit, cross agency interaction as well as different perspectives (e.g. terminologies, methods and motivations). Traditionally, practitioners, modellers and researchers tend to take one perspective from a single discipline to solve such problems, which limits the problem definition, promotes fragmentation and impacts the outcome, i.e. prevents developing resilient, innovative and efficient solutions. An alternative is to use an interdisciplinary approach, where multiple perspectives are integrated in modelling approaches iteratively. This paper presents an application using this approach to successfully incorporate EWRs in water resource modelling, where success is measured as all individuals confident in the representation and model output. It describes the challenges faced, the solutions developed and presents the learnings in order to set out a new direction when representing EWRs. We use the Tarago river system as a case study.

Before EWRs were represented, several problems and challenges were highlighted including (i) correctly interpreting the environmental flow requirements, and (ii) understanding the interconnectedness and complexities related to the seasonal and operational decision-making process. To gain clarity and identify the important elements, the main perspectives were firstly identified including the Tarago environmental water manager, water resource modeller, and operator. Secondly, to facilitate discussion and tease out the decision-making approach we developed a simple model. This and engagement with stakeholders using a combination of meetings, gaming examples and historical comparison identified integral factors governing the ecological health of the Tarago system – i.e. distribution of events and climate conditions. The model then was revised and documented. This approach provides for appropriate representation of EWRs, which is supported by stakeholders and provides a better outcome compared with traditional 'siloed' modelling approaches.

The benefits of using an interdisciplinary approach is that it provided an improved and comprehensive representation of how environmental water decisions are made in the Tarago system in an efficient and effective manner. It documents the decision space promoting transparency as well as knowledge retention, which is particularly important when individuals with experience and knowledge leave organisations. By engaging relevant perspectives at multiple points throughout the process, all parties had confidence in the modelling output and confidence when applying this information to long term water resource planning and operational decisions. The process also highlights the importance in engaging environmental water managers when integrating EWRs into a water resources model. Although this takes time and effort, it provided a mechanism to help facilitate discussions and brings further appreciation and understanding while creating robust and practical solutions. As problems become more complex it is imperative that modellers recognise and engage with key stakeholders and knowledge brokers to gain and build insights from different perspectives into models for developing integrated and innovative solutions. This case study highlights the benefits from this approach, while also acknowledging that there's a risk that unless this effective engagement occurs in model development, the most effective and resilient long term solutions will not adequately represent EWRs or be supported by key stakeholders and knowledge brokers.

Keywords: *Interdisciplinary approach, environmental water requirements, water resource modelling*

Assessing the sensitivity of catchment yields to changes in the frequency and timing of East Coast Lows: a case study in a coastal regulated river system in NSW

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Abstract: East coast lows (ECLs) are intense low-pressure systems that occur off the east coast of Australia. They can form at any time of the year, and significant ECLs occur on average about 10 times each year. Climate modelling conducted as part of the Eastern Seaboard Climate Change Initiative (ESCCI) projected a future with a decrease in the number of small to moderate ECLs in the cool season with little change in the frequency of small to moderate ECLs during the warm season. However, large ECLs are projected to increase in frequency in the warm season, but not change in the cool season.

Due to their large influence on rainfall characteristics, it is increasingly important to understand how changes in the frequency of ECLs may affect water security along the east coast of Australia. In this paper, we present the results of a case study undertaken to assess the impacts of potential climatic changes in ECLs, called ECL scenarios, on catchment yields in a catchment located in the South Coast of New South Wales. A stochastic model was used to generate stochastic climate data (rainfall and evaporation) under several plausible ECL scenarios. Historical climate data and stochastically generated data under the selected ECL scenarios were used to simulate runoff using existing calibrated rainfall-runoff models (Figure 1). Analysis of the non-linear relationships between climate variations and streamflow provides interesting insights regarding the influence of changes in ECLs on streamflow generation in spatial and temporal domains. We discuss implications spatial variance in sensitivity to ECL future climate scenarios for water supply security.

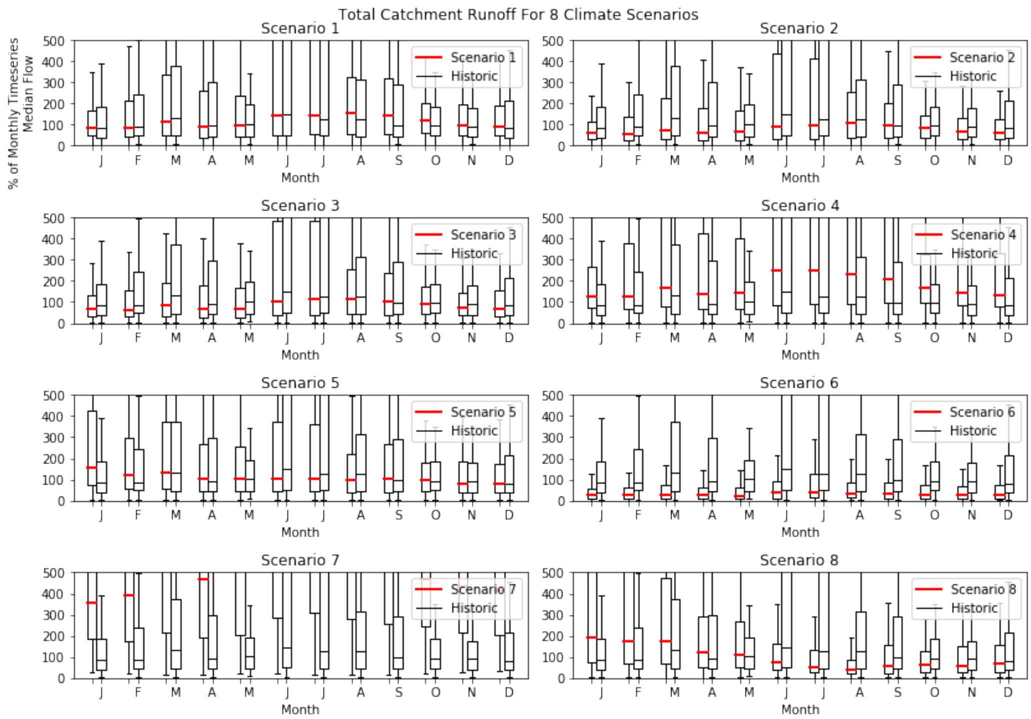

Figure 1. Monthly runoff for various ECL scenarios

Keywords: *East Coast Low, climate change, catchment yields, New South Wales South Coast*

A web application to estimate water extraction using a satellite-informed farm water balance model

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Abstract: The increasing scrutiny on water resources use has emphasised a lack in our capacity to accurately account for all groundwater and surface water flows and uses in water systems. Of particular interest is water extraction in the Murray-Darling Basin, where water licenses may allow irrigation farmers to divert of large volumes of river water into on-farm storages (OFS), and with some extractions being unmetered. Apart from increasing the on-ground metering network (e.g. with on-farm storage water level gauging), satellite remote sensing can also assist in estimating the amount of water extracted. The approach is to work backwards from variables that can be remotely sensed, which include the presence of surface water in storages and cropland conditions such as greenness, and estimate the storage changes, water losses and irrigation water application associated with those variables. The integration of all of these variables allows estimation of total property extraction volumes as opposed to crop water deficits that are met by irrigation.

We developed a web application that harnesses these satellite observations to estimate total water extraction volumes for any spatially defined property within the MDB. An important design criterion was to quantify rather than avoid the uncertainty associated with the various assumptions that need to be made in the process, by presenting a distribution of water extraction estimates that can be used to estimate the probability that total extractions over a defined period exceed a user specified threshold value. The web application relies on a back-end pre-processing system and a browser front-end analysis tool that allows the user to select input data and methods and change input assumptions. The back-end component routinely updates quality-controlled monthly composites of satellite greenness and wetness indices for a region of interest by processing satellite imagery from three alternative sources (Sentinel-2, Landsat series and MODIS).

The front-end component implements a farm dam water balance model that proceeds through the following steps in response to user input. (1) For each of the three satellite data sources, crop evapotranspiration (ET) is estimated using three alternative techniques: a satellite-based version of the FAO56 method, the CMRSET technique, and a simplified version on the Yebra-Penman-Monteith model. In each case, up to three alternative potential ET data estimates produced by the Bureau of Meteorology are scaled by a 'crop factor' that is derived from the satellite observations. This produces a maximum of 27 ET time series, providing an estimate of uncertainty in satellite-based ET estimates. (2) The user defines a period of interest, and provides the range and best estimate (or accepts default) values for a number of model parameters (change in soil moisture; OFS leakage rate and change in OFS water level; and irrigation water use, application and conveyance efficiencies). (3) A conceptually simple farm water balance simulation model is used to estimate all water requirements and losses, and from this total property water extraction volumes are inferred. The user input model parameters are then used to define a distribution from which equal-probability values are sampled in a multi-factorial approach. Combined with the ensemble of ET estimates, this yields a very large number of water extraction estimates that are presented in a histogram with user specified 'thresholds of interest'. The web application has so far been applied for more than 200 irrigation properties across NSW, and is currently undergoing evaluation and further development.

Keywords: *Water resources, water use, irrigation, satellite remote sensing*

EXTENDED ABSTRACT ONLY

State of the Kamala Basin: Co-producing knowledge to support water resources modelling and basin planning in Nepal

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Abstract: Nepal is rich in water resources, however the uneven geographic and temporal distribution of these resources restricts agricultural production as a pathway to broader development objectives and poverty alleviation. In 2018, the federal government of Nepal (GoN) commenced the preparation of strategic river basin plans across the country, precipitating the need for improved information, modelling tools, and processes to underpin these plans. In a context of rapid political change and decentralisation, it is essential that such innovations in planning are made collaboratively involving state and non-state stakeholders. Designed as a pilot case for national level basin planning, the Kamala Basin Initiative aims to develop a strategy for water resource management. The strategy is being developed as a collaboration between CSIRO, the GoN, and local partners Jalsrot Vikhas Sanstha and Policy Entrepreneurs Incorporated.

The co-production of the 'State of the Basin' (SoB) for the Kamala Basin in south-eastern Nepal is a key study to support the strategy. The co-production process included workshops, meetings, and focus group discussions with local communities, regional and federal government organisations. This process identified and prioritised issues and goals for future developments. Given existing limited data to support the SoB and strategy, primary data collection and modelling provided key inputs to facilitate the co-production process. Similarly, information and insights provided by stakeholders contributed in supporting the modelling analysis and strategy development.

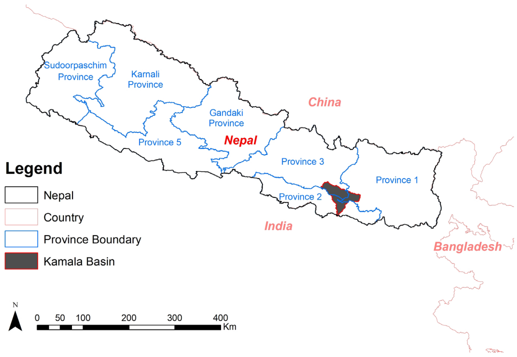

Figure 1. Nepal boundary and Kamala river basin

The Kamala Basin has a drainage area of 208,446 ha, elevation from 150 masl in the Terai to 2,200 masl in the lower/middle hills of Nepal (Figure1). It has a population of around 610,000 inhabitants. The Basin has a mean annual rainfall varying from 1,300 to 2,400 mm across the region with around 90% concentrated during the monsoon (June to September). The eWater Source model was used to estimate surface water availability and crop production across the basin, with more detailed crop growth and water balance modelling undertaken using the APSIM model. Additional socio-economic modelling was undertaken to support a participatory multi-criteria analysis. This modelling provided the basis for exploring alternative interventions to improve water distribution in the basin.

The SoB – to our knowledge the first such product for any river basin in Nepal – contains succinct information on critical issues. It presents data on monsoonal flooding, high sedimentation loads, water-based agricultural productivity and constraints, water quality, infrastructure limitations, labour limitation, social and economic indexes, water governance, water access and knowledge gaps. Synthesising current biophysical and socio-economic aspects of the basin allowed us to evaluate how water (un)availability impacts the local population and alternatives for future development and the regional economy and poverty alleviation. Information contained in the report has provided critical contextualization of a range of issues in the Kamala Basin. The report confirms the relevance of development goals and objectives formulated by basin stakeholders in a parallel complementary activity. This approach has been seen by GoN as an example to be considered in other basins in Nepal.

Keywords: *Water resources management, Basin Plan, State of the Basin, water availability modelling*

Water related risks and its management for agricultural development in Indian Sundarbans delta

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Abstract: The Indian Sundarbans located in the Ganges delta of West Bengal State of India represents a typical salt- and flood affected coastal deltaic region of South Asia. The Sundarbans region is one of the richest ecosystems in the world and home to 4.5 million people who often face severe poverty and vulnerability due to natural hazards. Village level vulnerability assessment revealed that the entire Sundarbans is highly vulnerable to climate change. About 60% of the population depends on agriculture for their livelihood, yet agricultural productivity is typically low. The resource poor farming communities, often face water-related risks like sea level rise (SLR), flooding with saline water, drainage congestion during monsoon (wet) season and lack of fresh irrigation water along with high soil salinity in dry season. SLR of Sundarbans in West Bengal coast is higher compared to other coastal regions of India, and over the last decade levels increased by 117 mm in West Bengal coast. Several kilometers of 3,500 km long river embankment created as flood protection measures in Sundarbans are now vulnerable to breaches and overtopping. The region receives about 1,818 mm annually of which 74% rainfall occurs during a few monsoon months causing widespread waterlogging of low lying lands. Though Sundarbans is intersected by intricate network of interconnecting waterways, there is water crisis in the region as the water in the rivers is mostly saline. The groundwater aquifers at shallow depths are quite saline, however, fresh water aquifers at depth of 160-400 m are beyond the reach of poor farming communities. Due to lack of fresh irrigation water and higher soil and water salinity, most of the agricultural fields are left fallow during dry season. Hence, the typical cropping intensity of Sundarbans is lower (128%) than in rest of West Bengal (185%).

This study reports on cropping systems and land management experiments in Gosaba Island aimed at demonstrating the potential to increase agricultural production in the area. Research experiments in farmers' fields indicated encouraging results towards higher cropping system intensification and profitability. However, availability of good quality and quantity of irrigation water and accessibility will in part determine the extent of adoption of such cropping systems. Maintenance of the existing embankments, raising embankment height and systematic retreat of selected embankments away from tidal channels are suggested for the stability of embankments, thereby protecting agricultural lands from sea water inundation. De-siltation of drainage channels, *beel* management in tidal rivers and proper maintenance of sluice gates connecting the internal canal network are essential to improve drainage. The excess rain water of this region, estimated as 2.7 times higher than crop evapo-transpiration in monsoon months should be harvested for creating fresh water resources. Different land shaping techniques like farm fond, deep furrow and high ridge and paddy-cum fish cultivation systems have been developed to suit different land situations, farm size and farmers' need. In land shaping farm land is modified primarily for harvesting rain water, reducing drainage congestion, reducing salinity build up and enhancing farm income through year round integrated crop-fish cultivation. About 12-25% land has been used for creating water storage structures having harvesting capacity of 1,400-4,600 m^3 ha^{-1} depending upon the techniques. Large scale implementation of these land shaping techniques over an area of 280 ha in Sundarbans has led to realization of 6-9 times more enhancement of farm income, increased cropping intensity to 193%, and more than 2.5 times household employment generation thus reducing out-migration. There is also greater scope of water harvesting by creating water detention structures using silted up canals/drainage channels/ relict or old creeks, building freshwater reservoir by partial or complete closure of estuaries. Success stories achieved through on-farm demonstration needs to be brought into larger policy framework through integrated assessment modeling by encompassing environmental quality, water use, risks and its rippling impact on agricultural production systems and overall socio-economic conditions of farmers.

Keywords: *Water risks, poverty, agricultural development, Sundarbans*

Understanding the impacts of short-term climate variability on drinking water source quality: sampling and modelling approaches

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Abstract: Climate change increases water-borne diseases especially in developing countries. Proactive climate resilient water, sanitation and hygiene (WaSH) interventions are designed to protect communities from increasing public health disease risks due to climate change. Centre to these WaSH interventions, drinking water sources are key to achieve improved public health outcomes. However, we currently lack understanding on how drinking water quality is affected by short-term climate variability across different types of water sources. This, in turn, limited our ability to predict drinking water quality, and to recommend climate-resilient water sources under a changing climate.

This study aims to address this gap by investigating the relationships between drinking water quality and variabilities in short-term climate conditions across different types of water sources. To achieve this, a 20-month observational study was conducted in Tanzania, aiming to capture changes in drinking water quality with short-term climate variability at various types of supply sources. Nine rounds of microbiological water quality sampling were conducted for *Escherichia coli (E. coli) and* total coliforms (TC), at three study sites (Buguruni, Kilombero and Kondoa) within different climatic regions (coastal tropical savanna, tropical savanna and warm semi-arid). Each round included approximately 233 samples from water sources and 632 samples from households. Various types of improved and unimproved sources were sampled, including piped water to premises, piped water at public taps, boreholes, protected and unprotected dug wells. The weather conditions at the three regions were also sampled continuously across the 20 months.

We then developed Bayesian hierarchical models to assess the impacts of observed changes in multiple climatic attributes on drinking water quality, across the various improved and unimproved water sources. Nine different climate attributes were considered in describing short-term variabilities in rainfall and temperature. The key findings are: 1) deteriorating drinking water quality is most closely related to increases in recent heavy rainfall consistently across water sources; 2) improved water sources (pipes and bores) are most climate-resilient, with water quality less affected by climate variability compared to the unimproved sources (dug wells). For the study regions, the study not only quantifies impacts of short-term climate variability on drinking water quality, but also suggests potential resilience of different water sources to future climate which provide valuable recommendations to future water and public health investments. The sampling and modelling approaches are also transferable for future studies to understand relationships between drinking water quality and climatic conditions in developing countries, which could assist further assessments of climate change impacts on water supply and public health. Our key recommendations to future studies of similar scopes are: 1) demonstrated value of high sampling frequency and temporal coverage (a minimum of 3 years) especially during wet seasons; 2) utility of the Bayesian hierarchical models to pool data from multiple sites whilst allowing for variations across space and water sources; 3) importance of a multi-disciplinary team approach with consistent commitment and sharing of knowledge.

Keywords: *Drinking water quality, E.coli, Coliform, East Africa, water supply sources*

Engaging small farmers and rural poor in modeling: Farmer Integrated Learning Model (FILM)

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Abstract: Developing mathematical models requires genuine engagement of communities for it to be practical, applicable and sustainable. For the past two decades scientists have come to recognize the value of working collaboratively. Yet, some key people remain outside the discourse and that is the small farmer, the poor and marginalised of all genders. Arguably these are the people with the lived experience of their environment. They have the "expert" knowledge and understanding of where they live, the challenges faced and importantly the opportunities that could be grasped to bring change. Building complex mathematical models may seem to outside the remit of poor and marginalised, often illiterate groups which has led to their exclusion.

Developing approaches to enhance farmer water management skills in Balochistan, Punjab and Sindh in Pakistan is a project funded by ACIAR designed to encourage small farmers to reduce irrigation and manage water and nutrients more sustainably which would increase crop production and enhance livelihoods of small farming families. It was also to look at how farmers learn to develop a scalable model of farmer to farmer learning and teaching.

With the belief that farmers and rural poor have knowledge which if different to but equal with that of scientists, engineers and adult educators the project sought a way of meaningful farmer engagement. Work in a previous project, the Agricultural sector Linkages Project showed that farmers trusted other farmers more than others. Underpinning the work was the Spriggs and Chambers (2011) on the Organic Research for Community Development Model (ORCD) and the notion of Asset Based Community Development (ABCD) developed by Kretzman and Mc Knight (1996) as well as the principles of adult learning. Three adult learning models were trialed, and evaluation of those models resulted in the integration of the best of each model into one – the Farmer Integrated Learning Model.

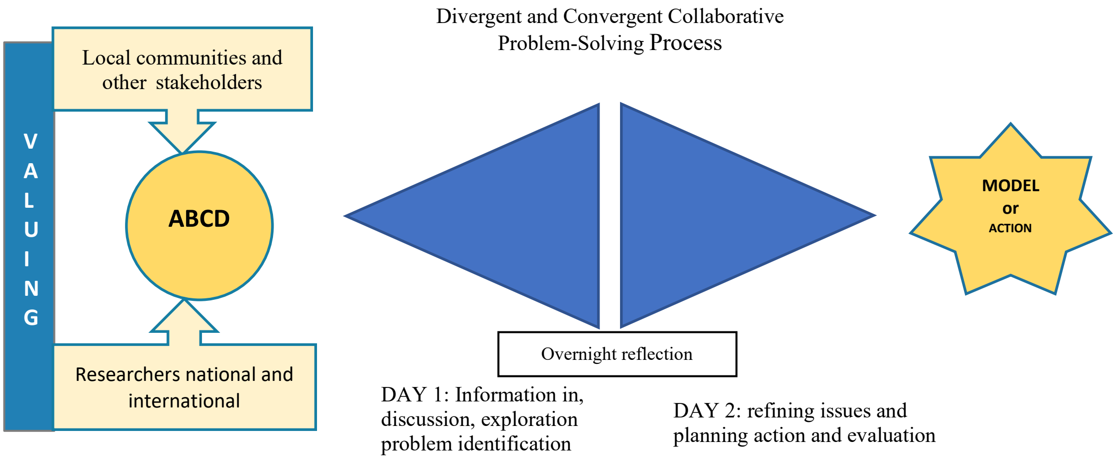

Figure 1. Farmer Integrated Learning Model

On further reflection on the success of the model to engage small farming families and particularly women the notion of the model being adaptable to purpose arose. FILM offers a way to engage all stakeholders from including farming families to address the challenges of the "agriculture, energy, water climate change nexus". Mathematical modelers can share their knowledge with farmers and how modelling can assist farmers to enhance their livelihoods and reduce poverty and farmers can add their knowledge to build realistic models for their context.

Keywords: *Engagement, community, adult education*

EXTENDED ABSTRACT ONLY

Who, what, where, when? Modelling cross-scale linkages between groundwater and household rice economies

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Abstract: Do the potential poverty-reducing benefits of groundwater infrastructure for supplementary irrigation trump the longer-term risk of drawdown that could threaten improved domestic water supply investments in south-east Cambodia? Understanding who benefits and who loses from investments in groundwater access, and where and when, is key to assessing both impacts on poverty and the potential for elite capture. Numerical models can be a valuable tool for integrating existing knowledge and data to better link catchment-scale, dynamic water resource availability and household-scale livelihood impact and adaptation. The multi-objective, multi-scale nature of the relationship poses a challenge that this research addresses via the development of a geospatial-linked Bayesian Network model (BN) to assess the impact of declining groundwater levels on the economics of rice cultivation for food security and cash cropping. Household livelihood outcomes are also considered with respect to the ensuing risk for groundwater-dependent domestic water supply. Initial discussions with ministry staff and government experts suggested disbelief in groundwater demand models that do not account for the effects of increasing pumping costs as groundwater levels decline. The BN was therefore designed to firstly consider groundwater irrigation demand across the full range possible given the spatially varied constraints on rice cropping and water availability mentioned during farmer interviews. Remote sensing and geospatial infrastructure mapping next linked these factors to the probability of a farmer investing in groundwater for irrigation and subsequent cropping patterns. The model finally calculates the most probable rice-related profit or loss outcome for a household under multiple groundwater level conditions. Validation was performed using a combination of commune database rice cropping results plus primary and secondary survey data from farmers. Exploratory modelling was subsequently undertaken to assess potential impacts of stakeholder-proposed policy mechanisms on irrigation demand and comment on the likelihood of ongoing private investment in groundwater given the significant environmental, infrastructural and market uncertainties involved.

Integrating the human-groundwater system across scales was a challenge that resulted in iteration between model structural complexity and the data available to populate it. The resulting model conceptualisation was designed for application and visualisation at a flexible spatial scale that allowed it to be easily linked to geospatial inputs and outputs. Nodes at the top of the model aggregate economic impact outcomes that might be experienced by households according to their land capital in order to provide some differentiation of 'who' in a village would be likely to benefit or lose from groundwater-irrigated crops, and by how much. Temporal considerations were handled both by designing the BN to represent household cropping options and consumptive rice requirements across a one-year timeframe, and by feeding the model with geospatial inputs and groundwater levels corresponding to various points-in-time along a given groundwater demand trajectory. Groundwater is typically touted for increasing the security of water supply and therefore empowering farmers to intensify their cropping and the farmer interviews confirmed this. The modelling however highlights the accompanying increase in likelihood of more extreme outcomes. As crops become more dependent on groundwater, the probability of both larger profits and significant losses increases, and a break-even outcome becomes less probable. Given the uncertainty associated with groundwater-irrigated crop outcomes, the model found that at under current market conditions there can be little leeway in rainfall before groundwater irrigators go into debt. Under conditions of water scarcity, farmers are unlikely to continue choosing crop patterns that promote groundwater drawdown. This result indicates a small likelihood that households will experience widespread domestic water shortages due to crop irrigation alone. Exploration of a range of potential water availability and price conditions that could result under ongoing and future policy initiatives however does identify scenarios where domestic wells would be at risk. The focus of stakeholder mental models on poverty reduction via agricultural productivity improvement may be allowing them to discount the possibility of future poverty risk due to competition for groundwater between crop irrigation and domestic water supply.

Keywords: *Integrated modelling, groundwater management, water poverty, Bayesian network*

An integrated assessment framework for examining the effectiveness of local water institutions

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Abstract: Environmental drivers such as climate play an obvious role in agricultural production and therefore have the potential to impact the livelihoods of rural communities. How these drivers play out are often intrinsically governed by social and institutional arrangements. In the case of the villages of Sekandarkhali and Khatail in southern Bangladesh, annual rainfall typically exceeds 2000 mm, yet freshwater availability during the dry season is a major constraint for increasing cropping intensities. Community owned canals exist but tend to be controlled by politically influential farmers who prefer the ingress of saline river water into the canal for their own benefit (i.e. shrimp farming). However, the majority of farmers are unable to use brackish water for cropping and domestic purposes. Without access to freshwater outside of the monsoon period, most farmers in these villages are unable to engage in agricultural production in the dry season. Many of those unable to secure annual food needs for their family through agriculture have to migrate seasonally for labour work outside their district. This out-migration by mainly young men has led to an increasing workload for women (i.e. feminization of agriculture).

This presentation explores the role of local water institutions in the livelihoods of the two communities. The study is part of a larger project aimed at promoting socially inclusive and sustainable agricultural intensification in West Bengal in India and Bangladesh. Local water governance committees (WSMC; Water and Silt Management Committee) were formed in the two Bangladesh villages, facilitated by our NGO partner with support from researchers. In each case the community, with help from the NGO, developed a constitution that outlines rules and regulations around the membership and operation of the WSMC. It aimed to represent all segments of the community, and build accountability and transparency in discussions and decisions on the maintenance, development and use of community water resources. Transparency increased following the establishment of the WSMC with the community engaged in decision-making and seeking information from our project partners and other stakeholders on financial matters, crop choice and water resource use. The community themselves contributed to the cost of developing and maintaining the water resource infrastructure. For example, 48% of the costs of the canal re-excavation in Sekandarkhali was shared by the community. More importantly, collective agency has emerged from the formation of the WSMC, with both communities gaining control of the canals and stopping the ingression of brackish water, through campaigns and negotiations with government officials. With freshwater now available and accessible to most villagers all year round, there has been a significant increase in cropping intensities. Farmers are now better able to generate income from agriculture, giving some the option to not migrate for work.

These case studies were examined using an integrated assessment framework, which maps out the key elements of water governance and distribution, and the causal pathways from interventions and drivers to the outcomes. This local water management framework is one of a series of connected components; the other frameworks cover the themes of inclusive value chain analysis, empowering change and livelihood aspirations. The water management framework was primarily based in the two Bangladesh case studies, but modified to be non-specific, so that it could be applied to other case studies on local water management. The integrated assessment frameworks were intended to form the basis for further qualitative or (semi)quantitative analysis.

In this presentation, we will provide an overview of the integrated assessment framework we developed for this study and describe how we applied it using Fuzzy Cognitive Mapping. We will discuss how the framework facilitated exploration of factors and issues involved with improving water availability, water quality and ensuring equitable distribution of water within the community.

Keywords: *Integrated assessment, local water management, research for development (R4D)*

EXTENDED ABSTRACT ONLY

Supporting water management in Nepal – Comparing options for water availability in the Kamala Basin

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Abstract: As part of formulating a river basin development strategy for the Kamala Basin, we describe the motivations for, design of, and outcomes of the first participatory multi-criteria analysis (MCA) in Nepal. Participatory MCA – a methodology to rank alternative options or management strategies – is sensitive to problem structuring, representation of interests, and quality of dialogue. We assess the effectiveness of MCA to guide stakeholder deliberation aimed at prioritizing options for water resource development for the Kamala Basin in Nepal.

The Kamala Basin in south-east Nepal is an important agricultural centre based around the Kamala Irrigation Project built by the Government of Nepal in the 1970s. The fertile lowland enables growing staples such as rice and wheat for subsistence. However, across the basin, agricultural livelihood outcomes are modest, and many working age men engage in long-term out-migration.

In 2018, as part of the first participatory planning initiative for the Kamala Basin (Figure 1), stakeholders formulated as a key objective the "conservation, development, and management of existing and potential water resources for improving consumptive use, and water use efficiency". Based on stakeholder input, four major options were identified to meet this objective: (1) revitalization of a 25,000 ha irrigation infrastructure; (2) increased groundwater use; (3) construction of small to medium reservoirs; and (4) construction of a large-scale inter-basin diversion from the Sun Koshi basin (proposed in 1985).

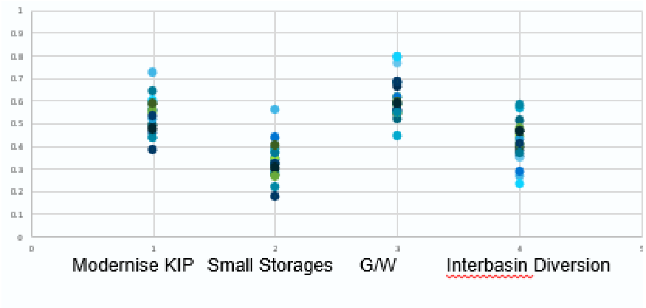

Figure 1. Preliminary utility scores for different development options. Each dot represents the response of a participant.

In May 2019, these options were compared by 23 participants from three levels of government and academia using ten evaluation criteria, informed by an evaluation matrix provided by the study team (based on desktop analysis, hydrological modelling, and expert interviews). Each participant assigned subjective weights to each criterion in two rounds of assessment. The criteria for assessing the options were: crop income (% change), ecological impact (rank), investment cost/ha, farmer affordability (water user charge), time to implement (rank), number of potential beneficiaries, percent marginalized beneficiaries, number of people with direct negative impacts, institutional and political complexity (rank), and performance against a future risk nominated by the participants. Based on the participant's weighting, the team presented utility scores back to the participants.

The utility scores obtained were counter-intuitive to many participants. Some findings challenged pre-existing beliefs about the strategic value of the inter-basin diversion scheme. Combined with the ability to visualize individual and group utility scores, the counter-intuitive results provided a catalyst to facilitate dialogue between participants representing distinct lower basin, upper basin, and federal government interests.

This report contributes to the South Asia Sustainable Development Investment Portfolio supported by the Australian aid program.

Keywords: *Multi-criteria analysis, IWRM, river basin planning, stakeholder participation*

Evaluating the effects of irrigation infrastructure on agricultural activities in the Kamala Basin, Nepal

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Abstract: Significant agricultural infrastructure development has occurred over the past few decades across Asia to enhance the availability of irrigation water, particularly in the dry season. Despite the linkage between water availability and improved agricultural productivity, the effectiveness of such infrastructural interventions may vary over time. This study, taking the Kamala Irrigation Project (KIP) in Nepal as an example, evaluates the effects of the irrigation infrastructure on agricultural activities during the dry season.

The study area is the Kamala Basin located in the south of Nepal. It covers the districts of Sindhuli, Udayapur, Dhanusha and Siraha and has a drainage area of about 208,446 ha at the Nepal – India border (Figure 1). Agriculture is the main economic activity and occupation within the basin. However, agricultural practices are mainly concentrated in irrigated crops.

The KIP project which was constructed between 1975 and 1980 is the largest irrigation system in the basin, with a designed irrigation area of 25,000 ha in the Dhanusha and Siraha districts. The water is diverted at the weir to two main canals, 27 and 31 km long in the west and east, respectively.

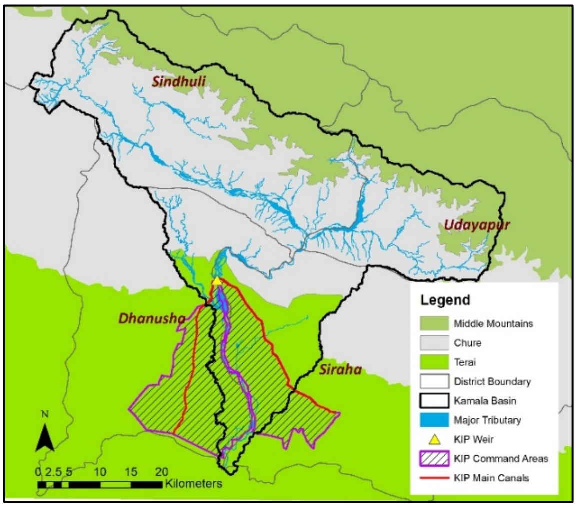

Figure 1. The map of the Kamala Basin and the Kamala Irrigation Project (KIP)

During the drier winter months, the water used by agriculture is dictated by crop selection and planted area. It is expected that variation in planted area to be an indicator of greater access to water, reflecting the effects of irrigation infrastructure. Based on the current district-level census of planted area, it is difficult to isolate variations in crop area due to the intervention. Hence, our study analysed remote sensing data and produced a higher resolution Village Development Committee (VDC)-level map of crop area in Dhanusha and Siraha in the Kamala Basin, between 1970 to 2016.

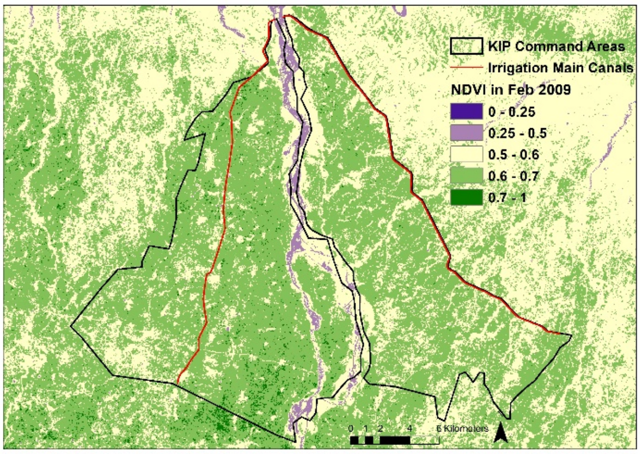

Figure 2. The normalized difference vegetation index (NDVI) in February 2009, from Landsat5 satellite imagery

Using satellite imagery, the crop areas along two main canals during the dry seasons were estimated by calculating the normalized difference vegetation index (NDVI). The region with values of NDVI between 0.6 and 0.7, for example in Figure 2, is classified as the crop area with an error of 4.5%. By comparing the variations in crop areas before and after the intervention, the impacts of irrigation infrastructure were examined. It may provide insights into the long-term effects of the intervention by assessing the changes of crop areas over different intervals, i.e. 5, 10, 15 and 20-year. Considering the study region would likely have received similar precipitation, maps of crop areas at the VDC level allow us to examine the spatial variations along the two canals within the irrigation system and capture the effects of the intervention. The temporal and spatial variations in crop areas can be used as indicator of the effects and performance of interventions.

Keywords: *Interventions, remote sensing, water availability, crop area estimation, dry season*

Desalinated water infrastructure optimization under competing trade-offs: A Chilean case study

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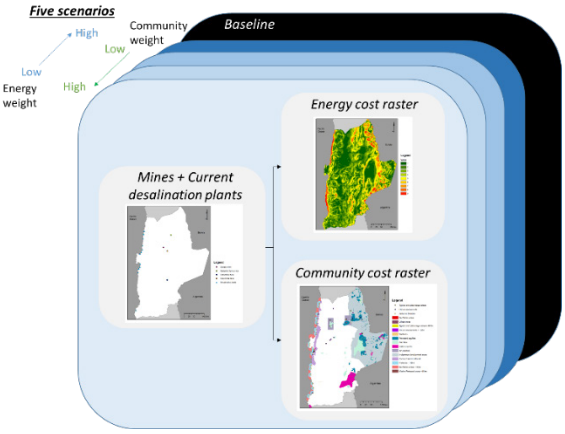
Abstract: Desalination is gaining attention as a solution to meet the water supply needs of mining operations located in water scarce regions. However, desalination expansion comes with trade-offs; including energy costs of treatment and transportation to mines at high altitude, and socio-environmental impacts associated with infrastructure. In this presentation, a regional-scale model is proposed for analyzing the competing trade-offs of desalination expansion through a case study in the Antofagasta mining region of Chile.

The model considers all "current" desalination plants that are approved, in operation or that are in construction for the purposes of supplying water to mining projects. The model[1] is implemented in ArcGIS, making use of the Spatial Analyst and Network Analyst toolboxes, and is constrained by topography and land use values. The model minimizes the relative cost of pumping water from the sea to each mining project according to the elevation change and horizontal distance required for infrastructure (Energy), and the extent to which desalination infrastructure interferes with competing land uses of most concern to local communities (Community). To investigate the sensitivity of the model to differing priorities, the relative weight assigned to the Energy vs. Community constraints was varied between 5 scenarios. Least-cost paths from desalination plants to mine sites were calculated using the Cost Distance tool in the Spatial Analyst toolbox.

Spatial datasets for the ArcGIS model were downloaded from publically available sources including IDE Chile, SubPesca, CONADI and CEDEUS. To generate the Energy cost raster, the slope of each cell was calculated from the digital elevation data and a normalized cost from 1-10 (with 10 representing the highest cost) was applied. Several steps were undertaken to generate the Community cost raster. First, the socio-environmental concerns raised by local communities during the mine approval process were identified through a review of Environmental Impact Assessments (EIAs) and an Environmental Impact Declaration (DIA) within the case study region. Communities were found to be most concerned about the influence of mining development on national parks, salt flats, wetlands, protected aquifers, air pollution (saturated and latent areas), indigenous development areas, historical monuments, urban areas, areas of scenic interest, and picturesque areas. Spatial datasets representing these different land uses were visualized. To generate the Community cost raster, each associated land use assigned a value based on the relative importance to local communities, and rescaled to a weighted cost raster ranging from 1-10. A buffer zone was also defined around fisheries and benthonic areas to restrict the locations of desalination plants to regions that would minimize socio-environmental concerns.



The model aims incorporate, in a quantitative manner, community constraints into the decision making process of desalination expansion design. The model provides a test bed for analyzing the cumulative effects associated with desalination expansion and for investigating scenarios to mitigate negative social-environmental impacts.

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[1] The algorithm advances Python code originally authored by: Maya Senzano, M.A., Keir, G., McIntyre, N., 2015. Mapping the feasibility of seawater supply to mining operations in the Second Region of Chile, in: Water and Industry - Water Week Latin America. pp. 96–106.

Keywords: *Water, energy, desalination, community conflict, mining sector*

Hydro-economic modelling of a mining catchment

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Abstract: Hydro-economic modelling is an established field of research that takes a multi-disciplinary approach to analysing water resources. This approach can be used to analyse water policies, assess impacts of changing climate conditions and explore synergies between water users. Hydro-economic models have been applied mainly to agricultural and urban water uses. The mining industry, despite being a relevant user in several catchments worldwide, has rarely been included. The aim of this project was to develop a hydro-economic model in the upper Aconcagua River in central Chile, to understand how this approach may support catchment-scale water decision making in regions where mining is an important user.

A conceptual semi-distributed model in WEAP was used as the water resources component of the hydro-economic model (HEM). The calibration involved the comparison of flows, snow water equivalents and hydro-power energy generation. The economic analysis included four water users: mining, agriculture, hydro-power and urban users. The coupling was done using Python scripts that connected WEAP with the economic functions. Three metrics were used to analyse water users: total value of water, shadow value of water and water scarcity cost. These three metrics provide different viewpoints from the water users in the catchment.

Three sets of scenarios were analysed. The first explored how changes in climate conditions may affect hydrology, coverage of users' demand for water, and the economic metrics. This scenario showed how small increases in temperature would generate changes in snow melting periods that may not be harmful, and even beneficial in some cases, to all water users.

The second scenario analysed the impacts of including minimum flow requirements in the catchment. Results showed that defining the magnitude of the restrictions and defining their location are equally important. It was also found that in this case study, the restrictions in the upper parts of the catchment had the largest economic impact, as they more affected the high-revenue industries, mining and hydro-power.

Finally, the HEM was used to analyse the shared benefits of a mine tailings water recycling project in the catchment. It was found that the economic value of the project for agriculture, urban and hydro-power users may not be very large, because of the allocation rules for the additional water. However, the exercise illustrated how HEMs can be used to evaluate the economic contributions that the mining industry can provide to other users by taking a catchment scale approach.

It is concluded that HEM can provide useful insights into the benefits and limitations of catchment scale approach to water resources management in mining regions. It was also found that a spatially detailed representation of the water resources component is important, particularly in areas where snow melt is relevant and where economically important extractions rely on small tributary flows.

Keywords: *Water resources management, hydro-economic modelling*

Assessing the cumulative impacts of coal resource development using surface and groundwater models

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Abstract: Environmental impact statements for new coal mines and coal seam gas projects as required by State and Federal legislation typically do not require proponents to assess the cumulative impacts of their proposed development in conjunction with other nearby proposed or current developments. Rather, the impacts of developments are typically considered in isolation, often because information on other developments may not be available or may be commercial-in-confidence.

To address this oversight, a 'water trigger' was added to the Australian Federal Government EPBC Act in 2013 that gave the Commonwealth regulator (the Department of the Environment) oversight of the direct, indirect and cumulative impacts of coal resource development on water dependent assets. As a result of the application of this water trigger, the Department of the Environment contracted the Commonwealth Scientific and Industrial Research Organisation (CSIRO) along with the Bureau of Meteorology and Geoscience Australia to undertake a series of cumulative impact assessments (known as 'Bioregional Assessments') to assess the potential cumulative impacts of coal mining and coal seam gas development across eastern Australia on water resources and water-dependent assets. These water-dependent assets include ecological assets such as wetlands or the habitat of endangered species, economic assets such as water access rights, and socio-cultural assets such as Indigenous sites. This presentation summarises some of the key findings of that assessment as related to impacts on surface and groundwater in the Gloucester, Hunter, Namoi and Galilee subregions.

Groundwater and surface water models of varying complexity were constructed and applied in all four subregions to assess the potential for proposed coal mines and coal seam gas developments to impact surface and groundwater as well as the assets that rely on them. A probabilistic framework was utilised whereby rather than calibrating an 'optimal' parameter set, a range of parameter values was examined which attempted to encompass the wide range of uncertainty in the potential hydrological response. Results were then presented as the outputs of the 5^{th}, 50^{th} and 95^{th} percentile changes in hydrology from this range of parameter values. For groundwater, drawdown in the regional aquifer was the hydrological metric evaluated, while for surface water, nine metrics reflecting changes in high flow, low flow and total flow were examined. In this presentation, increase in the number of low flow or zero flow days per year will be presented, as it was the surface water hydrological metric found to be most responsive to the impacts of coal resource development.

Results for groundwater indicate that drawdown in the regional aquifer in excess of 0.2 m is very likely at distances of up to 5 km from a coal mine. Drawdown in the regional aquifer in excess of 0.2 m is very unlikely at distances greater than around 20 km from a coal mine. Drawdown due to coal seam gas extraction generally occurs over a larger area than that due to coal mining but is generally of a lower magnitude.

Results for surface water indicate the potential for cumulative impacts moving downstream in all four subregions, however cumulative impacts tend to be minimised in the Hunter and Namoi rivers where releases from upstream dams maintain low flows. In the Gloucester subregion, cumulative impacts are seen on the Avon River, but are very unlikely downstream of the confluence with the much larger Gloucester River. In the Galilee subregion, cumulative impacts may propagate down the Belyando River and into the Suttor River, but are very unlikely to be seen below the Burdekin Falls Dam. These results indicate that the cumulative impacts of coal resource development should be considered in all four areas examined, namely the Gloucester, Hunter, Namoi and Galilee subregions.

Keywords: *Cumulative impact assessment, groundwater modelling, surface water modelling, coal mining, coal seam gas*

Residual Mass Severity Index (RMSI) – a duration free method to characterise droughts

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Abstract: The complexity of representing droughts has led to many drought indices being developed. A common aspect for many of these indices, however, is the need to adopt a predefined time-period, over which a drought is characterised. Therefore, to declare a catchment as drought impacted, 6, 12 or 24-month Standardized Precipitation Indices (SPI) are required. However, water supply insecurity has long been defined using the cumulative difference between inflow and demand, a concept known as the Residual Mass Curve. Here we propose a new framework to characterise drought, termed the Residual Mass Severity Index (RMSI). As the name suggests, the RMSI defines drought based on the magnitude of the residual mass in any location which is calculated by performing a water balance using a prescribed demand. Demand here is adopted as the median monthly precipitation for the region. Water shortages become significant only when there is a sustained deficit compared to this demand. The above described residual mass is standardised to formulate the RMSI across Australia. The new RMSI has been validated against established drought indices (such as the SPI) to highlight the advantages of a duration-free drought index. An assessment over known extreme historical droughts reveals RMSI as more consistent than SPI. An independent assessment of RMSI and its correspondence with hydrological drought is performed using streamflow data from 222 anthropogenically unaffected catchments of varied sizes, attributes and climates in Australia. Results again indicate that the RMSI classified periods of drought correspond to low flows consistently across the catchments considered.

RMSI provides a simple method of assessing sustained and severe drought anomalies which is important with expected increases in water scarcity due to anthropogenic climate change. We demonstrate that RMSI can be used as a tool to evaluate the performance of General Circulation Models (GMCs) in representing historical droughts in Australia from the Coupled Model Intercomparison Project 5 (CMIP5). The results of the model evaluation using the RMSI are compared to a previously developed wavelet based method that evaluates the skill of GCMs in correctly representing interannual variability. Future projections of drought from GCMs which perform well in representing RMSI in the historical climate are then compared to drought projections from the full CMIP5 ensemble.

Keywords: *Drought Residual Mass Curve, SPI, climate change, CMIP5 GCMs*

Centennial-scale variability of soil moisture in Eastern Australia

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Abstract: Soil moisture is of critical importance to maintaining agricultural productivity and is used as an indicator of agricultural drought. Antecedent soil moisture conditions are also important in forecasting catchment runoff and water storage levels. In-situ measurements of soil moisture, however, are exceedingly sparse at a global scale compared to most other hydroclimatic variables, and the temporal coverage of most records is limited to 15–20 years at best. To overcome this, water balance models have been developed and applied to evaluate soil water availability at centennial-scales. These include the Australian Water Availability Project (AWAP) Waterdyn model, and the Australian Water Resource Assessment (AWRA-L) models; two of the major water balance models used in Australia.

This study looks to extend on their validation and application using a unique in-situ soil moisture data set from the Scaling and Assimilation of Soil Moisture and Streamflow (SASMAS) project for the Krui and Merriwa River catchments in eastern NSW, Australia. The two catchments are predominantly grazed and can be considered representative of the wider East Coast of Australia. Modelled outputs were compared against catchment average in-situ data and validated using correlation analyses. Both models performed similarly across both catchments, with the AWAP upper and lower soil moisture layers returning correlation coefficients of 0.60–0.75, while the AWRA-L root zone layer returned correlation coefficients of 0.76–0.78. Following this, long term temporal trends in soil moisture anomalies from 1908–2015 were examined against trends in rainfall cumulative deviation. Soil moisture deficits and cumulative deviation of rainfall were well correlated from 1908–2015 ($r = 0.79$–0.84), as was shown by the response of soil moisture to major droughts across SE Australia. Across the entire timeseries, no significant trend could be found.

Many studies exist that look at this issue in response to the recent Millennium Drought across the Murray-Darling Basin, however, the East Coast of Australia is identified as its own separate climate entity. Understanding soil moisture trends in this understudied area, where agricultural, environmental and industrial water needs intersect is important. A key finding was that rainfall and soil moisture deficits were more severe during the WWII Drought than the Millennium Drought. This needs to be accounted for in drought management strategies.

Keywords: *Soil moisture, AWAP, AWRA-L, rainfall, agriculture, drought*

Lagrangian back-trajectory modelling to infer rainfall recycling and moisture sources in the Murray-Darling Basin

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Abstract: The relative importance of local versus remote processes affecting rainfall in the Murray-Darling Basin, particularly during drier periods, is uncertain. Where does the moisture come from, and how strongly do local land surface processes attenuate or amplify this atmospheric moisture to affect local rainfall? Establishing the evaporative source regions that supply moisture for rainfall can help reveal the mechanisms driving anomalously low rainfall. In the case of drought, it can help reveal whether anomalous rainfall was due to a reduction in source evaporation or anomalous atmospheric circulation (i.e., the moisture was generated but transported somewhere else).

We used a Lagrangian back-trajectory approach to determine the long-term average evaporative source regions that supply Australia's rainfall, and the level of recycling that rainfall undergoes. The back-trajectory model tracks water vapour from the location of a rainfall event backward in time and space to identify its evaporative origin. Back-trajectory parcels were launched at the location of rainfall events and were tracked using 10-minute time step, three-dimensional data on wind, temperature, precipitable water and air pressure. The data were linearly interpolated from the 50-km, 3-hourly NARCliM data set, which was spectrally nudged to ERA-Interim reanalysis above 500 hPa. At each time step a portion of the parcel's water vapor was assumed to have come from evaporation of the grid cell underlying the parcel at that point in its trajectory. Each parcel was tracked until all of the moisture at the original location of rainfall was accounted for. Moisture was tracked from every rainfall event across Australia for 1979–2013, yielding a two-dimensional water mass-weighted probability distribution of rainfall moisture source regions. From this, we calculated the proportion of rainfall falling across the Murray-Darling Basin that originated as evapotranspiration from the Basin itself; that is, the rainfall recycling ratio.

We combine this long-term baseline of source region and rainfall recycling with anomalies of source region evaporation and local convective available potential energy to investigate whether changing rainfall in the Murray-Darling Basin is likely due to changes to levels in advected moisture, source evaporation, land surface control on the atmosphere through feedbacks, or a combination of multiple factors.

Our results show a declining trend in moisture contributed to rainfall in the Murray-Darling Basin. In winter we found a declining trend in moisture from the Southern Ocean of over 100mm/year. Adding to this trend were further reductions, of smaller magnitude, in moisture contributed to winter rainfall from evapotranspiration from both within the Basin and the remainder of the Australian continent. We attribute the reduction in Murray-Darling Basin winter rainfall primarily to changes to atmospheric circulation during the winter season and subsequent levels of advected moisture available for rainfall generation.

***Keywords**: Rainfall recycling, source regions, back-trajectory, Murray-Darling Basin*

A wavelet-based method to analyse sustained hydrological anomalies under climate change

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Abstract: Industries and sectors affected by changes in water availability include agriculture, natural ecosystems, mining and domestic water supplies. Understanding the vulnerability of these systems to climate variability has traditionally been achieved by assuming that past hydrological extremes will occur in the future, an assumption that is no longer tenable due to anthropogenic climate change. Future sustained hydrological anomalies (e.g., sustained droughts) assessments have generally been based on General Circulation Model (GCM) simulations of precipitation, temperature, soil moisture, and so forth. However, firstly it is known that climate models with biases at a range of time scales have varying ability to represent sustained climate anomalies. Secondly, sustained droughts, for example, are natural hazards associated with a range of climatic factors such as sustained low precipitation, high temperature, strong winds, low relative humidity, and low frequency climate fluctuations (e.g., El Niño Southern Oscillation). It is a natural system consisting of the interaction among a large number of variables. Therefore, regardless of considerable uncertainty and bias in climate models, how to better model such a complex natural system is key to address all these climatic extreme events. In this study, we propose a wavelet-based downscaling framework to assess the sustained hydrological anomalies under climate change.

In the framework, given a set of observations (predictors) from a system, the goal is to first identify best possible drivers (inputs) from large numbers of climatic variables, form a predictive model based on the identified drivers, estimate the model parameters that best fit to the data, and finally predict the system response for new inputs. This approach is often limited by the internal variability and weak relationship between the response and predictors in climate system. To address these issues, we present a wavelet-based predictor selection and prediction method, which is based on two assumptions: 1) If the spectral variance structure of the predictor is similar to that of the response, the predictive model using that predictor will exhibit better accuracy (as measured by root mean square error, RMSE); 2) If the variance structure of the residual information contained within the predictor and response variable conditioned to the pre-existing predictor(s) is similar, the predictive model using the that predictor will exhibit better accuracy than otherwise. This method essentially reconstructs a new set of predictors by redistributing the variance in the spectrum of predictors. We assess the utility of the wavelet-based framework using synthetically generated data sets from known linear and nonlinear systems with parametric and nonparametric predictive models. A real application of predicting sustained drought anomalies over Sydney region confirms its utility in an applied setting. The results show clear improvements in predictability of the response compared to the use of unfiltered predictors.

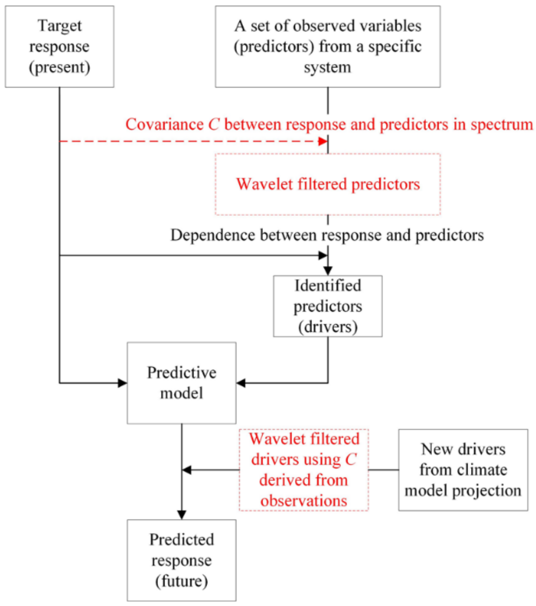

Figure 1. The proposed wavelet-based system modelling and response prediction framework

Keywords: *Wavelet transform, system modelling, prediction*

Exploring post 2011–12 drought in the Murray–Darling Basin

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Abstract: Drought, defined as rainfall deficiency, a familiar phenomenon in the Murray–Darling Basin, (the Basin) presents a risk to ecosystems, agriculture, industry and communities. The Millennium Drought from 1998 to 2009, with a peak from 2001 to 2009 (Bureau of Meteorology, 2015), was one of the longest and most severe droughts in the observed recorded history of the Basin. However, the Basin has experienced new intense drought conditions post 2011–12. In this paper, we use various climatic and hydrological variables including rainfall, soil moisture and streamflow to assess the severity of the drought in the Basin. Storage volumes and water market prices provide an indication of the impact of the drought on water availability.

Low rainfalls since 2012–13 led the Basin into drought. The contributing factors are a mixture of consistently rising temperatures and deficits in rainfall resulting in below average streamflows and declining groundwater and storage levels. During the July 2013 to June 2019 period; fifty per cent of the whole Basin experienced either severe or serious rainfall deficiencies. As a consequence, in the last 24-month period, soil moisture deficiencies were more than that during the most deficient 24–month period during the Millennium Drought. During the post 2011–12 period, 90 per cent of the gauges in Namoi, Gwydir and Border Rivers catchments of the northern Basin- recorded very-much-below-average flows.

The impact of drought on water availability is apparent from the total accessible storage volume across the Basin, which has declined to below 40 per cent by the end of 2018–19. In the northern Murray–Darling Basin, storage volume declined to nine per cent, a level as low as observed during the Millennium Drought.

Water market activity in the Basin is greatly influenced by the availability of water. During the low water availability years from 2012–13 to 2018–19 the demand for water rose and the price started to increase. In 2018-19, competition for very limited seasonally allocated water increased markedly, pushing the price up to record levels. Given the drought, prices for high reliability long-term water entitlements also hit unprecedented levels in 2018-19. Consumptive water use in the Basin declined when water availability was low and showed increased dependency on groundwater.

The post 2011–12 drought in the Murray–Darling Basin has in many ways been no less severe than the Millennium Drought; rather it can be considered as being more intense in many parts, especially in the north, even though up to the end of 2018–19 it may not have run its full course.

Keywords: *Drought, rainfall deficiency, consumptive water use, water trading*

Effects of soil data input on catchment streamflow and soil moisture prediction

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Abstract: This study attempts to investigate the impacts of soil data input on hydrologic model performance in simulating streamflow and soil moisture. Two different soil datasets available in Australia were considered: the Digital Atlas of Australian Soil (AoAS) and Soil and Landscape Grid of Australia (SLGA). We quantified the impacts of these two soil databases on hydrologic simulations using Soil Water Assessment tool (SWAT) model. Two separate calibration schemes were set up with two soil databases while keeping other inputs the same. For both cases, SWAT was calibrated to the daily streamflow at the catchment outlet over 2006-2012 (including wet and dry periods) and validated against the dataset over 2013-2015 (wet period), after 3 years warm up period (2003-2005). The soil moisture estimation from calibrated SWAT was then compared with the two radiometric satellite soil moisture products, the Soil Moisture Active Passive (SMAP)-Enhanced 9 km (L3SMP-E) and Soil Moisture and Ocean Salinity (SMOS) 25 km gridded (SMOS CATDS L3 SM 3-DAY) obtained during 2015. This study was conducted in Merriwa catchment, located in the upper part of the Goulburn River basin in Upper Hunter Region of NSW. The simulation results showed very little difference in streamflow prediction due to two different soil inputs. Both models showed very similar streamflow patterns (with similar NSE value of ~ 0.61 for calibration and ~ 0.45 for validation), but different soil moisture estimates. When catchment average near surface soil moisture estimates were compared with the satellite soil moisture products, SWAT calibrated with SLGA showed improved results (with R^2 value of 0.52 and 0.66 against SMAP-9 km and SMOS-25 km and RMSE of ~10 %) than that with AoAS (with R^2 value of 0.35 and 0.49 against SMAP-9 km and SMOS-25 km and RMSE of 18-22 %). The large differences in simulated soil moisture indicate importance of improved soil data input to capture soil moisture change patterns and significantly different water and energy partitioning for the catchment.

Keywords: *SWAT, streamflow, soil moisture, Soil and Landscape Grid of Australia, Atlas of Australian Soil*

Merging lidar with coarser DEMs for hydrodynamic modelling over large areas

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Abstract: Hydrodynamic modelling of flood flows requires accurate topographic data, which in most cases means lidar or photogrammetric data with proper separation of ground and non-ground features like vegetation. The entire modelling domain must be represented but the area of focus is often a small part of the entire domain, so it is often cost-effective to use expensive and detailed elevation data in the focus area and cheaper, less detailed data elsewhere. This leads to the need for joining the two digital elevation models (DEMs) seamlessly so that there are no abrupt changes in height or slope at the transition.

In the Fitzroy River of Western Australia, an area of 37000 km^2 was targeted for hydrodynamic modelling. Lidar data was collected in the floodplain area covering about 5800 km^2 and the remaining area was covered by SRTM-derived DEM-H at 1 arcsecond resolution. A method for adjusting the DEM-H to match the lidar data was developed to remove abrupt steps at the boundary to ensure the combined data was suitable for hydrodynamic modelling.

The two main steps in the process were (1) removal of systematic vertical errors and (2) adjusting the less reliable DEM-H to match the lidar at the boundary. The method successfully removed local steps and produced a result suitable for hydrodynamic modelling. There is scope for extending the adjustment process to account for broader scale differences.

Keywords: *Digital elevation models, lidar, blending*

EXTENDED ABSTRACT ONLY

The importance of topography in hyper-resolution hydrological modelling

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Abstract: Topography drives the terrestrial part of the water cycle, that is, water flows downhill. Nonetheless, the representation of topographical controls in large-scale land surface and hydrology models is often minimal. The coarse model resolution has generally allowed topography-controlled small-scale processes to be ignored or described in a conceptual manner (e.g., HBV, VIC). At the opposite end of the scale, hillslope hydrology models explicitly consider topographic control on lateral redistribution of excess rainfall (over and through the soil and in the local groundwater system, e.g., TOPOG). However, their computational requirements and a lack of observational constraints has meant they have rarely made it beyond case studies.

This is changing as the discipline converges towards 'hyper-resolution' modelling; primarily because of rapidly increasing computational resources, and supported by a proliferation of spatial data (e.g., remotely sensed topography and vegetation dynamics). For example, the AWRA-L model is used by Bureau of Meteorology to simulate daily time series of multiple decades over a domain of >10^5 grid cells (0.05° across Australia). ANU has applied a very similar model at 0.05° globally (W3v2, >10^6 elements) and at ~500-m across Australia (OzWALD, >10^7 elements), including grid-based river flow routing. This was made possible by the National Computational Infrastructure. We anticipate achieving 25-m resolution across most of Australia within the next four years.

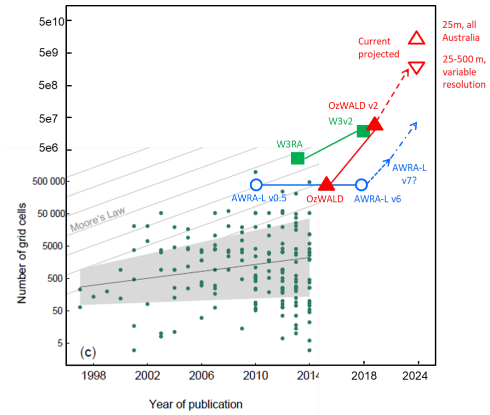

Figure 1. Trend in the number of spatial model elements in VIC-model studies (Melsen et al., 2016) showing that hyper-resolution modelling over large domains is becoming increasingly feasible. Superimposed the version traces of BoM AWRA (open blue dots) and ANU's Australian (red triangles) and global (closed green squares).

Increasing resolution supports finer-scale spatial parameter and forcing data, and in many cases does not require model re-conceptualisation. This is often not true for topography-controlled variables and processes, however. We discuss relevant experiences in applying the AWRA-lineage of models as resolution increases, relating to: (1) downscaling meteorological variables using a digital elevation model; (2) simulating topographical controls on soil hydraulic properties and processes (e.g., infiltration and deep drainage); (3) simulating lateral redistribution on hillslopes; (4) using hypsometric relationships to simulate surface-groundwater interactions (e.g. saturation, evaporation and root uptake of groundwater); and (5) grid-based river flow routing.

Based on experiences for Australia and globally, the AWRA conceptual structure, which conceptualises grid cells as one (or several parallel) small catchments with uniform properties and forcing, generally still produces conceptually reasonable results as resolution is increased to 500-m (25-ha), except in very mountainous regions and in river floodplains. Downscaling climate forcing data can be beneficial, however, and hypsometric curves and routing grids at the higher resolution can change model behaviour. At 25-m, the model conceptualisation of lateral flow processes can become inappropriate and processes such as run-off/run-on and hillslope groundwater dynamics may need to be considered. Priorities for research and development are suggested.

Reference: Melsen, L.A., et al., 2016. HESS Opinions: The need for process-based evaluation of large-domain hyper-resolution models. *Hydrol. Earth Syst. Sci.* 20: 1069-1079.

Keywords: *Topography, hyper-resolution modelling, hydrological processes, downscaling*

Open data based exposure assessment of flash floods in high-density urban areas

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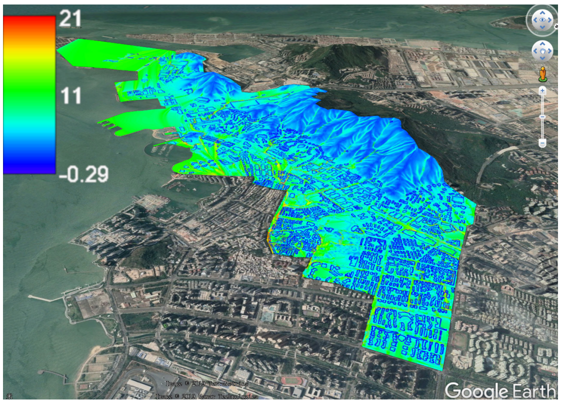
Abstract: Rapid urbanization in China is placing increased pressure on urban drainage infrastructure. Northeast coastal cities are susceptible to flood damage from typhoons and climate change is expected to produce more extreme weather events. Urban planners and local governments need better risk assessment tools to plan for future extreme events.

An exposure assessment model has been developed to assess the risk of flash flooding in urban areas under future climate scenarios. The proposed model is based on hydrological simulation, which accuracy is sensitive to the precision of input digital elevation model (DEM). A regression kriging based geo-interpolation method is employed to reshape ground surface by increasing precision of global coverage ASTER DEM from 30m to 10m. Time component is introduced to the Horton's water permeation model. The parameter of permeation speed limitation is critical to this model; initial values are taken from published Land Classification Codes and adjusted according to the field surveys and observation records.

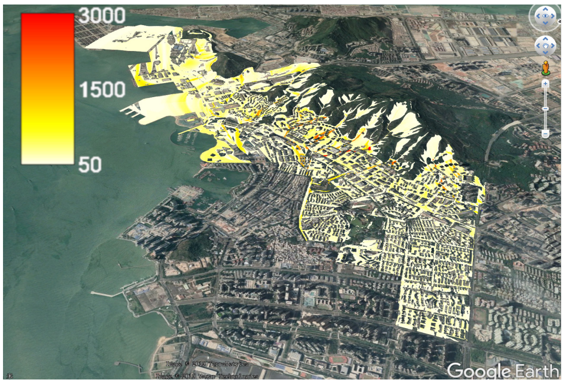
This research is focused on using free and open source data for modelling. Besides the ASTER DEM, high resolution Google Maps satellite RGB imagery is used for urban surface analysis. VVI (Visible Vegetation Index), TGI (Triangular Greenness Index) and GLI (Green leaf index) are used for vegetation detection and cross validation. Building footprints, road networks, waterways and drainage networks are drawn from public data. Weather records and extreme rainfall data are from local meteorological bureau web site. The model construction, calculation and simulation is developed in an R language environment.

Shekou community in Shenzhen is a case study to illustrate the proposed model for flash floods exposure assessment, see Figure 1. Urban wetness index (UWI) is calculated based on modified urban catchment area analysis using a slope-weighted multiple flow direction method, see Figure 1 (a).

To examine the performance of this proposed model, two most common scenarios are tested. One scenario is a storm at low-tide condition, with a fully functional urban drainage system. This scenario is simulated by using historical rainfall data from Meteorological Bureau. Figure 1 (b) shows a simulated maximum accumulative depth map (mm/hr) calculated using the average value of all maximum precipitation records in August of 1995-2015. The other scenario is a typhoon occurring at high-tide, which means urban drainage system is partially malfunctioned by outer water pressure. Some of the simulation results show agreement with satellite observations. Our future work will focus on modelling water pressure impact caused by high tides.



(a) Urban wetness index distribution



(b) A simulation result of runoff in August

Figure 1. A Case Study of Shekou in Shenzhen, China

Keywords: *Exposure assessment, flash floods, high density city, open data solution*

Modelling approaches to estimate environmental water contribution in the Murray-Darling Basin

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Abstract: Basin Plan (the Plan) for the Murray-Darling Basin (MDB) came into effect in November 2012. One of the major purposes of the Plan is the management of Basin water resources in a way that optimizes economic, social and environmental outcomes. The Plan also establishes and enforces environmentally sustainable limits on the surface and ground water take from the Basin water resources. Buyback of irrigation entitlements by the government from willing sellers is the main vehicle to achieve the water recovery targets and to reach the diversion limits that are mandated in the Plan. About 2000 GL of surface water has been progressively recovered since 2012 towards bridging the gap and majority of it is held by the Commonwealth Environmental Water Holder that manages it to achieve various environmental outcomes in collaboration with other state based environmental agencies and the Murray-Darling Basin Authority. Environmental water entitlement holders operate under the MDB agreement just like other irrigation water entitlement holders. The performance of environmental agencies is assessed by evaluating the environmental outcomes of their actions. Measurement of flow contribution by environmental actions at key locations is considered as the best first order evidence of fair share of those actions in improving river health. However, given the complex and highly regulated nature of the MDB and operational constraints and rules estimating the actual flow contribution made by environmental water use at a given site is a great challenge and a complex problem.

Recently, the Plan has come under greater scrutiny that whether it is meeting its environmental objectives. It is required to accurately estimate the contribution of environmental flows at various locations to address those concerns. Various approaches applied to estimate the environmental water contribution in the River Murray System during last few years include:

1. **Evidence Based:** For example, investigating causal links between watering actions and increase in birds breading or fish population,
2. **With and Without Environmental Water Approach:** The environmental contribution at a given site is the difference between modelled flows with planned environmental releases included and the modelled flows without environmental releases. For "without" case delivered environmental flows are assumed taken out of the system,
3. **Pre-recovery Approach**: The environmental contribution is the difference between long-term modelled flows assuming no environmental water recovery and modelled actual flows. The pre-recovery model run assumes that all water available in the system is for consumptive use.

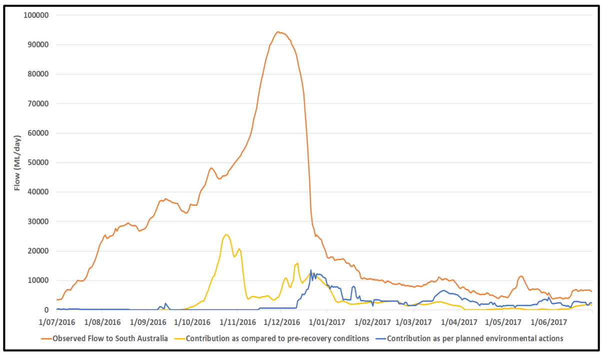

Figure 1. Approaches to estimate environmental water contribution

Results of Approach 2 and Approach 3 are discussed in this article e.g. modelled environmental contribution to flow to South Australia (Figure 1). The two approaches are quite different in terms of modelled environmental water contribution. The blue line in the plot (Approach 2) represents environmental delivery to South Australia for 2016-17. This approach suits well to sites which are accounting points for environmental flows and serves best to evaluate short-term/annual performance of environmental watering actions. In reality, various other factors like storage spills would have contributed too. The orange line is the Approach 3 representing the difference between modelled flows under pre-recovery and current conditions since 2012. This approach models continuous impact of the long-term water reform, e.g. the additional contribution during Oct – Dec shows system's response from previous actions. It is concluded that use of either of the approaches is quite context specific. For example, Approach 2 does not have memory of previous years and suits well to short-term analysis whereas Approach 3 suits best to analyze relatively long-term impact of the water reform.

Keywords: *Basin Plan, water recovery, modelled environmental water contribution*

Non-climatic trends in gridded climate data

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Abstract: Climatic data are a key input to models of rainfall-runoff, urban demand, crop water requirements and farm dam impacts, which in turn are key inputs to water resources modelling. Historically inputs to these models have been derived from at-site gauged rainfall, temperature and Class A pan evaporation data. Recently a range of gridded climate data products have become available through the Bureau of Meteorology (BoM) (AWAP and AWRA-L) and Queensland Government (SILO). Use of gridded data avoids the need to infill and extend at-site data, and allows data to be extracted at a point or over a catchment area capturing greater variability, particularly with respect to topography. This paper explores the use of gridded climate data for water resource modelling in South East Australia.

The SILO gridded data set was selected as it extends back to 1889 and so includes the Federation Drought; AWAP/AWRA-L data commences in 1900 or later. Gridded rainfall and temperature data compared well with concurrent at-site data. Advice from literature (McMahon et. al, 2013) was used to determine the best gridded evaporation data set to use for each application. Morton's shallow lake evaporation was used to represent evaporation from storage, FAO 56 reference crop evapotranspiration was used to determine crop water requirements, and Morton's wet-environment areal evapotranspiration over land (MWAE) was used as input to rainfall-runoff modelling, undertaken using the GR4J model in Source.

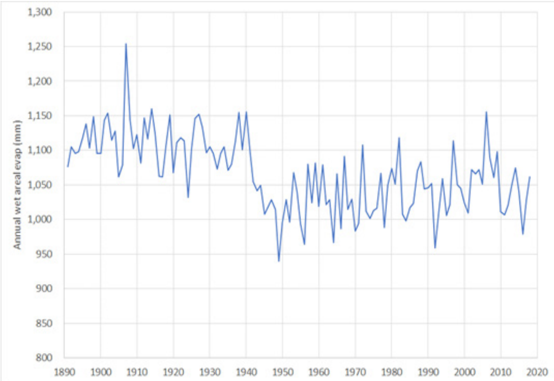

Figure 1. SILO annual Morton's wet areal evapotranspiration over land (example catchment)

MWAE is derived as a function of sunshine hours, temperature, relative humidity, latitude, elevation and rainfall. It was found that higher values occur in the early part of the record (Figure 1) which in turn influenced the inflows generated by rainfall-runoff modelling.

Prior to 1957 selected SILO data sets are generated using the CLIMARC data set which is based on approximately 60 stations across Australia (Rayner et. al., 2004). Examination of maximum temperature data at the station closest to the example site shows that this station is driving the trend in MWAE. Examination of other concurrent recorded temperature data shows higher temperatures during this period at some but not all locations. Non-climatic trend can be created by changes to the recording equipment used, or changes in site location or conditions. Ashcroft et. al. (2012) notes a shift from less sheltered recording equipment to Stevenson thermometer screens after Federation, and concluded that there is no appreciable difference between temperatures during the Federation Drought and those typical of the first half of the 20th century. Non-climatic trends in temperature records were removed as part of the creation of the Australian Climate Observations Reference Network – Surface Air Temperature (ACORN-SAT) data set (Trewin, 2012). Data prior to 1910 was not used due to the lack of Stevenson screens prior to this date. Examination of AWRA-L evaporation data shows that non-climatic trends are not present due to the use of ACORN-SAT data.

Rainfall detrending removes non-climatic trends from at-site gauged data by comparison with a nearby BoM high quality rainfall gauge. Gridded rainfall data was compared to a nearby BoM high quality rainfall gauge. It was found that the SILO gridded rainfall data retained some trend, but the equivalent AWAP rainfall data set showed detrending had been undertaken.

In conclusion, the SILO gridded data set is an extremely useful data source when deriving inputs for water resource modelling, particularly where the Federation Drought must be included, but care must be taken when using some data types including temperature, radiation, vapour pressure, and data sets derived using these variables, particularly over the earlier period of record. There is also the potential for embedded non-climatic trend in SILO rainfall data.

Keywords: *Rainfall-runoff modelling, gridded climate data, Morton's wet areal evapotranspiration*

Long-term inflows for Namoi Valley

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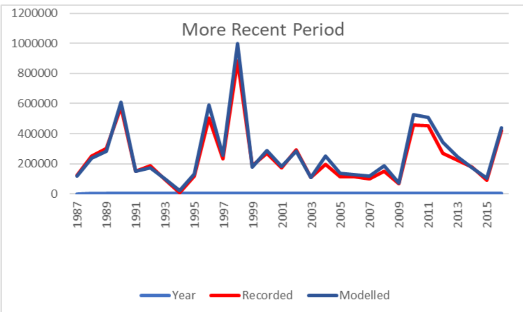
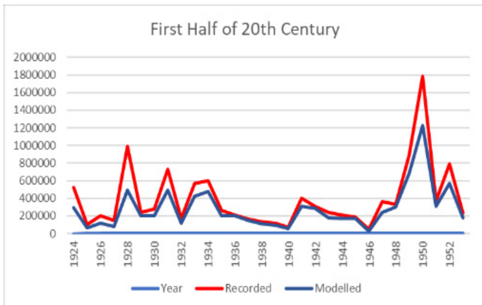
Abstract: The eWater source modelling frame work has been used for rainfall-runoff calibration across the Namoi River Catchment. Calibration Scheme includes optimisation of multiple objectives that covers different aspects of hydrology such as overall water balance, shape of hydrograph, high flows and low flows. This paper investigates the results obtained from Sacramento model to simulate the streamflow across more than 20 sub-catchments of Namoi valley. The 1911-2018 gridded rainfall and evaporation data obtained from Bureau of Meteorology (BOM) for each sub-catchment is used to estimate the long-term daily runoff across the region. The daily recorded flows available for calibration purpose ranges in variable periods for different sub-catchments.

The most recent period ranging within 1970-2018 was used for Sacramento rainfall-runoff model calibration. The results indicate that the current conditions of most catchments are significantly changed from early part of last century. Where long-term records were available, the Sacramento model predictions were significantly less in early to middle of last century. The comparison of aggregated sub-catchments with the main river records also showed similar trends.

The results of this study indicate that several Namoi sub-catchments are not stationary. When those sub-catchments are integrated and inflows at Keepit Dam generated, the model predicts significantly lower flows in first half of 20th century at the dam site (pictures below). It is therefore important that the long-term inflows to be used in planning models should be generated purely from rainfall-runoff models. The current practice of merging of recorded where and when available, and rainfall-runoff modelled inflows may lead to inaccurate conclusions.





Keywords: *Rainfall-runoff model, long-term flows, planning model, trend*

Source adoption in Northern Victoria: a hydrological model of an integrated Goulburn, Broken, Campaspe, Coliban and Loddon Rivers system

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Abstract: Surface water models are fundamental in providing the evidence to inform policy and investment decision making to sustainably manage water resource planning and operations. The Victorian Department of Environment, Land, Water and Planning (DELWP) is committed to ensuring that future water planning and management are informed by using best practice modelling. eWater Source, a key deliverable of the Australian National Hydrological Modelling Strategy, is designed to simulate aspects of water resource systems in a consistent, transparent and defensible manner. The development of a daily timestep Source model for the Northern Victorian catchment of the Goulburn, Broken, Campaspe, Coliban and Loddon (GBCCL) Rivers has been one of the key elements of Victoria's transition to the eWater Source software platform.

The GBCCL catchment has the most complex operating and water sharing arrangements in Victoria to meet the consumptive and environmental demands of rural and urban water supply systems. A daily timestep Source GBCCL foundational model has now been successfully configured to simulate the water supply system of the Goulburn, Broken, Campaspe, Coliban and Loddon Rivers including the Waranga Western Channel and East Goulburn Main Channel systems. The model has been developed using daily data inputs that cover more than 120 years over the period from January 1891 to June 2014 and generally represents a level of development based on conditions in 2009 with the most up-to-date information. The model simulates multiple sources of water supply under various water management and operating rules, bidirectional flows, storage capacity sharing between water corporations, urban restrictions, annual accounting resource assessments for five sub-systems and carryover rules.

Adopting commonly used graphical techniques for overview of a model performance, the Source GBCCL model results are compared with historical records using time series, exceedance and cumulative plots for the period from 1994 to 2009. Given the model generally represents a level of development based on conditions in 2009, differences are expected when compared with historical records. Despite some differences, the comparison of storage volumes, flows and seasonal determinations between the modelled and the observed generally shows a good agreement.

Similarly, the Source model results also compare with the results from the existing model of the system, the monthly timestep Goulburn Simulation Model (GSM) developed using the REsource ALlocation Model (REALM) software. They are also generally close for all sub-systems although some differences exist, which will be further investigated and explained. Furthermore, there are some recommended improvements to be made to the Source GBCCL model in the future.

The foundational version of the daily Source GBCCL model is currently configured as a planning model with complex annual accounting resource assessment systems. With further improvements, it can be utilised for compliance purposes as well as a tool for assessment of policy and management options, and the possible impacts of options on the water supply systems. If a need exists, the model could be modified and extended to be an operational tool in the future.

The successful implementation of Source for the integrated GBCCL system, a key pillar of Victoria's transition to the Source modelling platform, demonstrates that Source can be a 'fit-for-purpose' modelling platform to replace the existing REALM software. This has also provided confidence for transition from the REALM to Source modelling platform in Victoria.

Keywords: *Source adoption, hydrological modelling, water resource management*

Global spatial layers enable rapid water resource assessment in data-sparse regions

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Abstract: River basin modelling provides vital information to support water resource management. These models can depend on high quality data. Data sets that are limited, not for purpose or poor-quality are often a barrier to use of river basin modelling in developing countries. Key inputs for rainfall-runoff modelling include sub-catchment boundaries, rainfall, potential evaporation and functional unit areas. This paper presents an approach for using spatial data analysis to support water modelling in data sparse regions, focussing on case studies in two countries; Lao Peoples Democratic Republic (Lao PDR) and Afghanistan. In Lao PDR, the approach has been used to support the Ministry of Natural Resources to draw together information about the issues, challenges, opportunities and trade-offs for water resource availability, to support the preparation of the National Water Strategy. In Afghanistan, the approach has been used to develop a Source model for a rapid assessment of all major basins in Afghanistan.

The approach included Geographic Information System (GIS) analysis to create the sub-catchment boundary from a Digital Elevation Model (DEM) needed to underpin rainfall and runoff models in Source. Satellite Rainfall Estimates were obtained from the CHIRPS (Climate Hazards Group InfraRed Precipitation with Station) quasi-global rainfall dataset to be used as the rainfall inputs for Source modelling. WATCH global temperature data was used to calculate potential evaporation using the Hargreaves method. The Climate Data Input tool in Source can create daily climate time series in each sub-catchment automatically from input raster climate data.

Sub-catchment boundary and climate data was used to develop a geographic catchment model easily via the Source platform. The final product was a calibrated rainfall and runoff model of sufficient quality to provide baseline information and a high-level assessment of water management challenges and opportunities. This 'rapid-assessment' approach, combining freely available satellite data, spatial analysis and programming to analyse and process model inputs, can increase the use of water modelling to support better water management in data-sparse areas.

Keywords: *Source, data-sparse, GIS and Spatial analysis*

Impact assessment of drought, climate change and development in a highly regulated arid basin

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Abstract: Located on the fringe of the Atacama Desert in southern Peru, the Caplina-Locumba basin (16,389 km^2, Fig. 1) presents a range of challenges for sustainable management of water resources. Surface water resources are limited during average climate conditions, situation that worsens during severe periods of low rainfall. Water scarcity can affect a wide range of users (population, mining, industry) and impact about 25,000 ha under irrigation. To overcome situations of temporary deficit, the basin is highly regulated, with inter-basin transfers, reservoirs with limited capacity and groundwater extractions from El Ayro aquifer (located in the Andean Plateau, with an average annual precipitation of ~ 400 mm per year) to the city of Tacna (346,013 inhabitants) and the valley of Tacna (2,067 ha irrigation).

Monitoring of flows, volumes in reservoirs and groundwater levels in aquifers and forecasting potential changes in these (climate, infrastructure development), and mitigation measures to reduce impacts on users were assessed through a Water Resources Management (WRM) model, built in eWater Source. The Caplina-Locumba basin model has 576 links and 867 nodes and was implemented on a daily time scale scale for the period 1981-2011.

The calibration and parameterisation were performed using observed streamflow at 23 gauging stations, volumes in reservoirs, and water demand data, reflecting the current operating rules. The river system was calibrated by sections (i.e., between control points where there are gauging stations, dams or offtakes), verifying that the simulated flows were satisfactorily reproduced in terms of timing and volume. The calibration was considered successful, with an average NSE 0.46 (-0.70-0.85) and absolute bias of 11.26% (-39.26-28.64%). If not considered highly regulated stations, the average NSE rises to 0.59 (Fig 2a). In the case of stations used for model calibration, the average NSE is 0.74 (0.62 to 0.85) and 11.27% absolute bias (-23.31-28.64%). An important aspect was the model's capabilities of both reproducing high and low flows (Fig. 2b) and that reservoir volumes are comparable to observed ones. As anticipated, in stations where historical operating rules were different from today, it was very difficult to reproduce streamflow accurately. Also, records were short (two to five years depending on the station) to attempt a calibration with current operating rules.

The WRM model implemented adequately described the hydrology of the water resources system for a variable climate, included existing (or future) operational rules, and (existing or potential) water-sharing protocols The calibrated WRM model was used to: (i) underpin the development of a drought management plan for the basin, (ii) assess potential impacts of climate change, (iii) infrastructure development and (iv) improvements in irrigation efficiency.

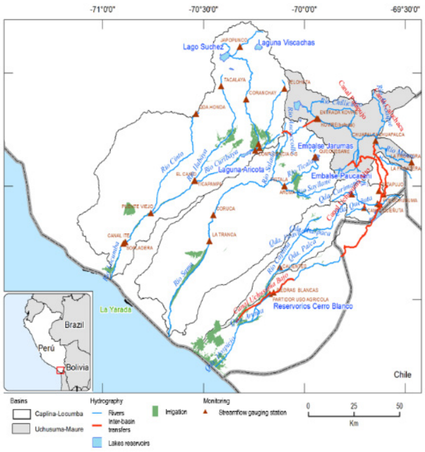

Figure 1. Location and characteristics of the Caplina-Locumba Basin

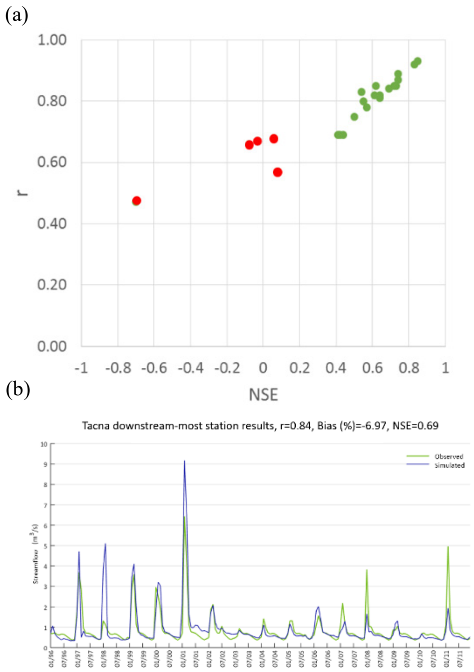

Figure 2. (a) GOF for the 23 simulated stations (red dots indicate high regulation), (b) example of modelled and simulated streamflow

Keywords: *Drought, water scarcity, hydrologic modelling, Peru, water management*

Modelling infiltration and exfiltration in MUSIC

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Abstract: Losses through exfiltration from stormwater treatment devices in MUSIC models do not reflect realistic infiltration through soils and associated water quality improvements. Water NSW has developed a novel approach to model the realistic effect of in-situ soils on water quality improvements under various soil types and rainfall conditions.

Water NSW used its Wastewater Effluent Model (WEM) (i.e. an effluent plume generation model) to predict how far pollutants would travel in various soil types before the nutrients reach background or natural concentration levels. The WEM determined maximum areas required to treat exfiltration from the stormwater treatment devices under various soil types and rainfall zones that could be claimed or used in MUSIC models. A number of MUSIC modelling scenarios with media filtration or infiltration node connected via secondary drainage link as shown in **Figure 1** were run to determine the pollutant reductions that can be achieved from infiltration through natural occurring soils.

The modelling results indicated that (i) model with media filtration or infiltration node linked with secondary drainage reflects water balance more accurately, (ii) there was consistent pollutant reduction irrespective of soil type and rainfall zone, and (iii) the overall pollutant reductions improved approximately 1%. Whilst this provides a small benefit, it will be beneficial for achieving a neutral or beneficial effect on water quality (NorBE) for developments within Sydney drinking water catchment that are close to achieving NorBE.

Based on the findings, Water NSW updated manual "Using MUSIC in the Sydney drinking water catchment" in 2019. The manual provides guidance on applying the media filtration node and/or the infiltration node connected with a secondary drainage link to model the infiltration from stormwater treatment devices through naturally occurring soils. The guidance information aims to ensure that this is done correctly and realistically.

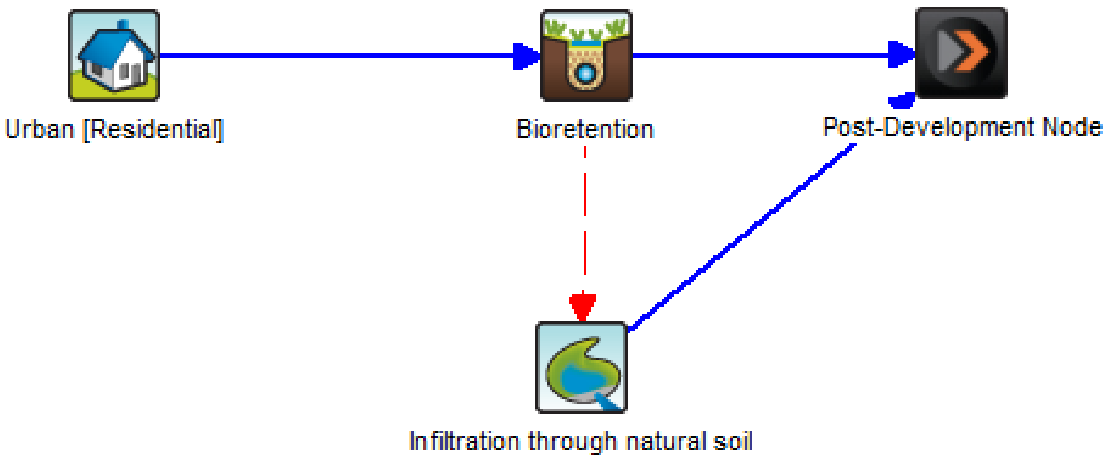

Figure 1. Example of modelling infiltration through naturally occurring soil

Keywords: *NorBE, secondary drainage link, plume generation model*

MUSIC-X for integrated urban water modelling

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Abstract: Catchment urbanisation leads to increased contaminant loads into receiving waterbodies. Depending on the nature of pollutants, different treatment measures are needed to improve stormwater quality. It is important to access the performance of these stormwater treatment measures. MUSIC (Model for Urban Stormwater Improvement Conceptualisation) has evolved to be one of the strongest Integrated Urban Drainage Models capable of simulating both quality and quantity of catchment runoff from single allotment to many square kilometres. MUSIC can model the effect of a wide range of stormwater treatment options to achieve Water Sensitive Urban Design (WSUD) goals.

While MUSIC is a widely popular tool for designing an integrated stormwater management system, there is scope for improving the capabilities of this model. MUSIC does not include all aspects of stormwater management that decision makers must consider particularly in the context of Integrated Water Cycle Management. It is a highly conceptual model and therefor any detailed design and analysis of the urban stormwater system is inhibited at the present stage. Furthermore, there are a limited number of pollutants that can be modelled. Adding new scientific understanding into the model framework is difficult because it is not a very flexible model. The lack of flexibility could cause MUSIC to become obsolete in future use.

MUSIC is a standalone model. So, it is difficult to integrate MUSIC with other integrated water management tools in the present version.

Considering all these limitations, there is a need to further develop MUSIC. This paper presents MUSIC-X which is the new generation model. MUSIC-X will offer

- network validation.
- a broader range of pollutants with an ability to model additional contaminants such as hydrocarbon and heavy metals
- improved Rainfall-Runoff modelling options with flexible time steps
- direct linkage to Bureau of Meteorology database for speedy model building process
- functionality to assess and determine fulfilment of frequent flow management objectives that contribute to reducing directly connected imperviousness, thereby improving waterways ecology
- functionality to allow MUSIC-X models to be linked to river System and other urban water models.

These improvements enhance the capacity to model and develop Integrated Water Cycle Management. These capabilities of MUSIC-X create an opportunity for modelling interactions in urban drainage, water supply and eventually broader integrated water resource management. Ultimately, this will benefit the entire water industry with particular emphasis on Local and State Government Authorities where MUSIC is currently utilised.

Keywords: *Integrated water management, WSUD, MUSIC, MUSIC-X*

Using eWater Source to support Integrated Water Resources Management in Lao People's Democratic Republic

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Abstract: Water plays an essential role in the life and culture of the Lao people. More than a third of gross domestic product and 75% of total employment are from subsistence agriculture, which is heavily reliant on rainfall and fluvial water resources.

Traditionally, Lao PDR was considered a water-rich country. This is changing, with:

- increasing demands on water resources
- competition between water users, especially in the dry season
- impacts of climate change on water quality and water management infrastructure.

In response to these challenges, the government of the People's Democratic Republic of Lao (Lao PDR), is implementing a series of major water reforms to support sustainable and integrated water resource management. To support these reforms, the World Bank's Mekong Integrated Water Resources Management (MIWRM) program is supporting the Lao PDR to establish good examples of integrated water resources management (IWRM) practices at the regional, river basin and local levels.

eWater Source has been used to build and calibrate models in four MIWRM demonstration river basins, the Xe Kong, Xe Don, Xe Bang Hieng and the Xe Bang Fai. The models have been used to:

- evaluate total water availability from surface runoff, and where relevant inter-basin transfers)
- assess domestic, industrial, hydropower and agricultural demands
- assess water availability for environmental purposes and downstream users (basin outflows)
- consider the impacts of different water resource development scenarios on natural flow patterns, especially dry season water availability
- consider the impacts of the different water resource development scenarios under a climate change.

The project produced fit-for-purpose models that supported water resource assessment in the four test river basins and scenario analysis in the Xe Kong Basin.

The work is intended to guide and inform the development of a full scenario assessment based on a detailed understanding of water resources development pathways in Lao PDR, tailored to the specific needs of Lao PDR water resources decision-makers.

Importantly, the eWater Source platform was shown to be an effective tool for working in low-data environments such as Lao PDR. The adaptive nature of Source will allow for additional data to be added as it becomes available, thereby progressively increasing the reliability and accuracy of the analysis.

Through the capacity building components of the project, the NRERI Hydrological Modelling Unit now has the capability to configure eWater Source model scenarios for the four basin models, to inform future planning option assessments and support basin planning.

Keywords: *eWater Source, Integrated Water Resources Management*

Refinement and application of the Source Murray model in South Australia

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Abstract: Simulation models underpin information and advice provided to support policy and management of the water resources in the River Murray and Lower Darling system. These simulation models are required due to the complex physical characteristics of the Murray-Darling Basin and water sharing rules defined in the Murray-Darling Basin Agreement, and continual evolution of operation of the river. A hydrological model of the River Murray and Lower Darling River has been developed by the Murray-Darling Basin Authority (MDBA) using eWater Source and is referred to as the Source Murray Model (SMM). A number of reviews have concluded that the SMM is fit for purpose and an improvement over previous models and it is being used to develop water resource plans for the River Murray,

However, as currently configured, the SMM does not include a number of existing structures in South Australia, such as locks and weirs. These structures are being managed to restore some natural variability in water levels. A model capable of representing the change in flow and additional losses from these actions is desirable. Additionally, construction of infrastructure on the floodplains for environmental benefits within the South Australian section of the River Murray has commenced, which is also desirable to represent in the model for future applications.

Therefore, additional development and refinement of the South Australian part of the SMM was initiated within the South Australian Department for Environment and Water (DEW). The proposed developments will improve DEW's ability to:

- Assess various water quality, quantity and potential hydro-ecological changes within an environmental water planning and infrastructure operations scenarios
- Simulate both site and cumulative environmental risk and/or benefit under the suite of potential infrastructure operations within the SA River Murray.

To refine the SMM, numerous scenarios were modelled using hydrodynamic models (MIKE FLOOD) to provide a wide range of conditions Results from these hydrodynamic scenarios (such as flows and operational water levels) were used to parameterise and calibrate the hydrological model. Calibration was undertaken by adjusting routing parameters to provide accurate representations of the area and volume outputs for each reach simulated through hydrodynamic modelling. For the wetlands, conveyance relationships on wetland links were also calibrated using the outputs of the hydraulic model scenarios to achieve the required water surface elevation between the river and wetlands. Subsequently, the calibrated parameters (i.e. rating curves, travel times, storage dimensions, and conveyance relationships) were validated against historical records from 1977 to 2018. The statistics demonstrate that the SA River Murray Source Model can simulate downstream flows at Lock 1, and water level at Lake Alexandrina and Lake Albert, with high accuracy throughout the modelled period.

With this model, the capability now exists to simulate a range of operational scenarios considering weir pool manipulations and operation of floodplain infrastructure currently under construction that was not previously possible. The SA SMM model is used extensively to support both short and long-term South Australian environmental water planning, lake level management, and barrage release strategies by aligning proposed watering actions across multiple sites to maximise the environmental objectives that can be achieved for a given volume of environmental water available.

Keywords: *River Murray, eWater Source, weir node, water resource planning*

Modelling salinity registers using the Source Murray Model

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Abstract: Management of salinity continues to be a significant challenge in the Murray-Darling Basin. It has adverse implications for water quality, agriculture and water supply. The Basin Salinity Management 2030 Strategy (BSM2030) provides a continuation of the joint management framework between the Murray-Darling Basin Authority (MDBA) and state governments to prevent a return to the highly saline conditions of previous decades. Central to the BSM2030 strategy is the register of salinity credits and debits to keep account of actions that increase salinity in the river system, so they can be offset by actions, implemented elsewhere in the system, which decrease salinity. This accountability by Basin governments ensures on-going management of salinity in the basin to reduce adverse impacts on industries and the environment.

The MDBA has configured the Source Murray Model (SMM) to be used to calculate the salinity impacts arising from accountable actions on the River Murray and estimating salinity register items. The baseline scenario for calculating the register uses inflows, concentrations, and unaccounted salt loads that represent the 1988 level of development. The baseline scenario is then adjusted incrementally for each register item to represent changes in policy, management or land use practices until it represents contemporary management and behavior. The SMM is run over a benchmark climatic period (1975-2000) for each registry entry and the indicators used to estimate the cumulative salinity impacts are a change in average and 95th percentile salinity at the River Murray Morgan gauge (426554), and the associated economic costs to water users.

A key feature in developing the registers is the ability of the SMM to calculate the historical unaccounted salt loads. Examples of unaccounted salt loads include saline groundwater inflow, salt accumulated on floodplains and washed into the river during high flow events and unmeasured drains. Source is able to calculate the historical unaccounted salt loads by undertaking a reach calibration comparing two scenarios. The first assuming no unaccounted salt loads and the second assuming a salt load of 1 ton/km/day along the reach. Using the information generated from the Source marker method to track salinity, the unaccounted salt load can be calculated to ensure a good model fit to the reaches downstream observed salinity. The historical unaccounted salt loads can then be adjusted in the registry entries to model the impact of salinity management interventions such as salt interception schemes.

Keywords: *Salinity, salt load, Source*

Australian WaterTools: Three national platforms supporting the management of Australia's scarce water resources

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Abstract: Australia is an internationally recognised leader in water policy development and water resource management under scarcity. Fundamental to this has been a commitment to evidence-based decision making, achieved by investing in tools and methods that support the collection, analysis and presentation of water related data.

The Australian Government is committed to sharing its experience, tools and methods to assist other governments build their capacity in water resource management and to address the issues of changing climates and increasing water scarcity. To this end, the Australian Water Partnership has supported eWater, Geoscience Australia and the Australian Bureau of Meteorology to produce *Australian WaterTools: Three national platforms supporting the management of Australia's scarce water resources.*

The guide showcases three tools that are shaping Australia's future direction for managing its scarce water resources:

- eWater Source – Australia's National Hydrological Modelling Platform, a planning and operational hydrological modelling tool which integrates hydrology and the policy/legal dimension.
- Digital Earth Australia (DEA) and Open Data Cube (ODC) technology for organising remotely sensed information into analysis-ready forms to identify water availability and use.
- The Bureau of Meteorology Forecasting Tools and the associated Australian Water Resource Information System (AWRIS).

The guide includes a pilot project that tested the feasibility of using the three tools to produce new hydrological drought metrics for the United Nations Economic and Social Commission for Asia and the Pacific (UN ESCAP) Regional Drought Mechanism Cambodia pilot.

Traditionally, estimating water availability rely on comprehensive on-ground gauging networks measuring rainfall and streamflow. Such networks are limited in Cambodia. A Cambodia Open Data Cube was built to house relevant space-based data. The Bureau of Meteorology produced bias-corrected rainfall and streamflow forecasts that were fed into the data cube, these and other data was then used by eWater Source to estimate water balance and flows.

By working together, the three tools produce water availability estimates of an acceptable quality. The process does not replace long term reliable records from ground stations, but in circumstances where observed data is limited it can provide water managers and users with more information to base decisions on. Further, it could support water managers to collect more data at less cost by helping to prioritise where to install on-ground networks.

Connecting the water forecasting tools and Source to the Cambodia ODC allowed many of the inputs for the Source model to be automatically generated, dramatically reducing the time required to build the model, and potentially making modelling more accessible to water managers.

A publicly available interactive internet dashboard was created to communicate drought and water availability metrics. Providing information on low water availability risks, in a relatively simple format, to a wide audience via the internet, has the potential to significantly improve water management, at all scales, from basin managers to individual farmers.

Keywords: *eWater Source, Open Data Cube, water forecasting, water scarcity*

Considering water quality with quantity for optimal management of water resources

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Abstract: Challenges faced by water resource systems are numerous. They typically include variable and changing climatic conditions, variable water quality, increasing demand for water, and problems associated with old and aging assets. Scarcity of good quality water is particularly a serious problem faced by many regions in the world. The problem can be even more pronounced in a dry continent like Australia where the water resources can often be afflicted by high salinity, turbidity and blue green algae. Therefore, modern water resource systems require appropriate management of both water quality and quantity. This paper describes a study which aims to use modelling techniques to inform the trade-offs between optimal water quantity and quality objectives in the reservoir. The Grampians reservoir system (Mala-Jetmaraova et al., 2015, Godoy et.al. 2009) is chosen as the case study for this research as it is sufficiently complex and includes many of the contemporary water resources challenges seen around the world. The system supplies an area approximately 10% the size of Victoria, consisting of nine interconnected reservoirs, weirs and regulating structures.

Australia has long history of addressing complex water related issues using different decision support software tools. Mostly, simulation software is used to model water balances and undertake water resource planning activities. However, optimisation algorithms are now being used to help with better understanding of the complex tradeoffs and decision making. The software Source® is a good example of modern software platform which integrates both simulation and optimisation capability (Ashbolt et.al. 2011) and has been used in the current study.

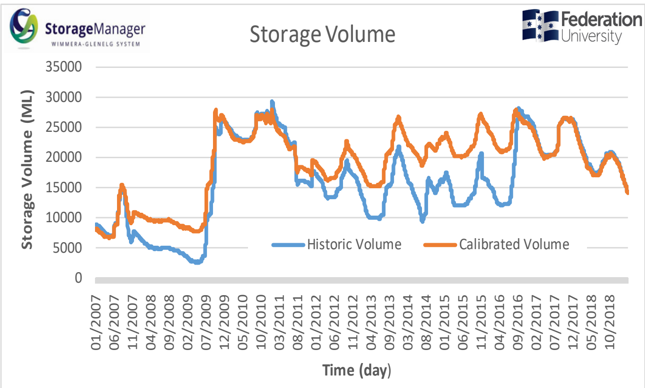

Figure 1: Preliminary results for the daily modelling of Taylors Lake.

To date, research has commenced with the development of a daily time step water balance model of Taylors Lake, one out of nine reservoirs of Grampians system. Taylors Lake has a complex combination of possible inflows able to be harvested into storage which can affect its water quality. Initial work starts with building a simple water balance model. Preliminary results are shown in Figure 1 and despite some initial calibration efforts, still requires some further refinement in order to produce more accurate representation. Access to good quality data remains an issue. In time, the Source® model will be extended to incorporate both water quality considerations as well as overlay an optimisation process to see what positive impacts the operating rules can have to maximise water availability for the end users. This paper presents some early work. Final outcomes of this research will focus on building a conceptual model to help the water managers to efficiently manage the water systems by minimising the trade-offs between optimal water quantity and quality objectives considering inflow and outflow of water in the reservoir.

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Keywords: *Complex water resource system, Grampians water system, Source®, Water quality*

A flexible and intuitive approach to water resource modelling: Otway Source Model case study

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Abstract: In the face of an uncertain climate future and population growth, water managers will need to depend on effective tools to help them make decisions about the management of precious water resources. Water resource models provide valuable decision support tools to help manage our water resources in terms of simulating the impacts of changes to water supply (volume and quality) and changes to urban demands. Moreover, such models are quite useful in providing insights on the timing of future system upgrades and associated energy consumption implications. Therefore, it is important that these models are sufficiently flexible and robust to evaluate the broad range of water resource management scenarios. It is also important to clearly document and communicate how to navigate, run and update these models, so that they are effective as decision support tools. The Otway Water Supply System (Victoria, Australia), is an ideal case study where a flexible and robust model was developed within eWater Source to enable the operator (Wannon Water) to consider a range of demand, climate and augmentation scenarios.

We present techniques for 'soft-coding' model inputs and parameters within the eWater Source function manager, to provide a more flexible approach to scenario modelling (Figure 1). We also present examples of how to incorporate advanced functions, using bilinear and context variables, to minimise unnecessary duplication of functions across the model. We demonstrate how these functions can be referenced in 'Scenario Input Sets' to streamline the overall model structure, while alternating between groups of input data and parameters. This modelling approach resulted in the creation of one 'master' model of the Otway system, with the functionality to model a diverse range of scenarios, including greenhouse gas emissions, climate change, demand growth, water quality, storage augmentation, network upgrades, storage targets and water restriction curves. The ability to simulate a wide range of scenarios using one 'master' model streamlines future updates and quality control processes leading to improved model transparency.

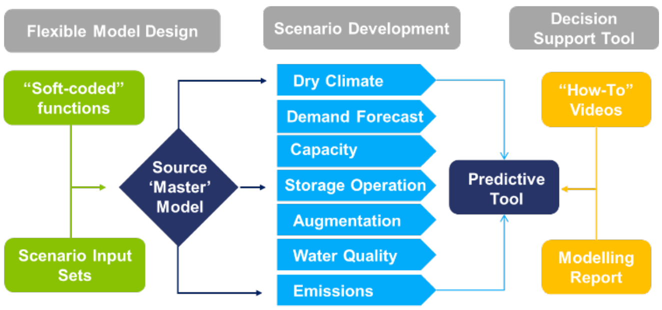

Figure 1. Flexible modelling process

In this case study, we provide an alternative approach to model documentation, through creating a series of customised 'how to' videos which demonstrate how to maintain, update and simulate the Otway Source Model. We also highlight the power of visual communication through incorporating animated schematics of the water supply network and aerial drone footage within these videos to quickly develop a shared understanding of the key features of these water supply systems and how they are represented within the model.

The key outcome from this study was the development of a more flexible and robust water resource model of the Otway Water Supply System, combined with visual communication tools to help manage water resources in the face of an uncertain climate future and population growth. This modelling approach has broad and wide-ranging applications across the water resources field, particularly in terms of the development of effective decision support tools.

Keywords: *eWater Source, water resource modelling, decision support tool, visual communication*

Transforming modelling data into decisions: Interactive dashboards for eWater Source

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Abstract: Water resource models provide valuable decision support tools to help manage our water resources; however, visualising and presenting the vast amounts of data produced from these models is a challenge. Moreover, communicating the large datasets generated from model simulations to a group of stakeholders and regulators is also difficult. Therefore, it is important that model simulation datasets are presented in a clear and visually appealing manner that can be easily understood and interpreted, so the true value of using water resource models as decision support tools can be realised. The Daylesford Water Supply System Dashboard (Victoria, Australia), presents the ideal case study, where an interactive, flexible and visually appealing dashboard was developed to communicate results from the eWater Source model configured for the system. The dashboard was configured to present modelling results alongside other core business information to quickly create a shared understanding of the system and provide flexibility in presentation of data.

We present methods for visualising model output datasets using interactive dashboards developed within the Microsoft Power BI interface (Figure 1). We also present examples of how you can incorporate climate data, and the system configuration, to create a broader overview of the results, which can be used to develop key insights. We show how you can develop a flexible data model to accommodate additional data, added scenarios or variables which may need to be considered. This approach to visualising data had the added benefit of presenting data in a hierarchical form over multiple dashboard report pages, which allowed the user to deep dive further into the information. This aspect was useful during stakeholder engagement workshops, allowing stakeholders to better understand the results across the system.

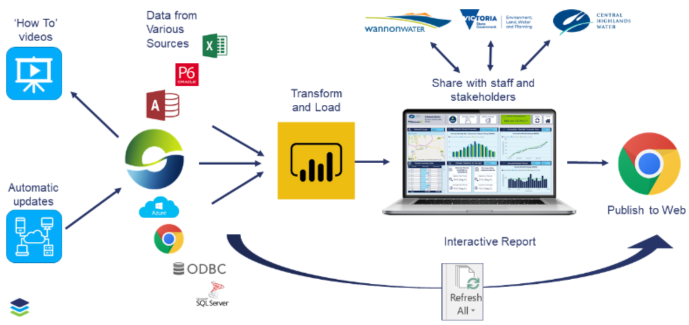

Figure 1. Interactive Dashboards for eWater Source

In this case study, we provide an alternative approach to presenting eWater Source model results by developing an interactive dashboard for the Daylesford System. We highlight the power of visual communication through incorporating multiple pages within the dashboard report, and showing how you can use various sources of information to draw key insights into the model results and build an enhanced shared understanding. We also show how these dashboard tools are a substitute for the traditional lengthy, PDF reports and are an effective decision support tool that can be used in stakeholder engagement workshops.

The key outcome from this study was the development of an interactive dashboard, which was considered to be a more flexible and robust method for communicating results from the eWater Source model simulations of the Daylesford System. This approach to data visualisation and presentation of information in a clear and engaging manner, was shown to be a more effective decision support tool during stakeholder engagement workshops, and has broad and wide-ranging applications across the water resources modelling field. More information on this study is provided in this short video summary: https://youtu.be/KshTTWLAy_0

Keywords: *eWater Source, interactive dashboard, water resource modelling, decision support tool, visual communication*

Modelling the implications of reduced return flows due to irrigation efficiency improvement projects in the southern Murray–Darling Basin

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Abstract: The Murray–Darling Basin is currently undergoing one of the biggest government investments into irrigation efficiency in history, driven by implementation of the federally legislated Basin Plan (2012). Improvements to irrigation efficiency are known to have indirect effects on non-consumed run-off and groundwater seepage from farms, also known as 'return flow'. A recent University of Melbourne study quantified the reduction in return flow across the Murray–Darling Basin due to government investment in irrigation efficiency projects. The study identified a long term reduction in return flows of 121 GL/y, of which 24 GL/y is reduced surface run-off and 97 GL/y is attributed to reduced groundwater seepage. The reduction in groundwater seepage will develop progressively over the next 20-60 years.

The implications of this reduction in return flows on water users should be considered in context of the existing water accounting and sharing rules in the Basin. The water accounting and sharing rules in the southern Murray–Darling Basin are among the most complex in the world.

We have prepared two model scenarios which, via comparison of their results, allow for some analysis of the implications of reduced return flows in the southern Murray–Darling Basin. The two scenarios were developed using the Source Murray Model. The Source Murray Model is a daily time step node-link model, first constructed in 2015, that represents the sharing, management and physical distribution of water. The baseline scenario we use represents conditions just prior to the Commonwealth's investment in irrigation efficiency projects across the Basin. A second scenario was created to reflect the 121 GL/y reduction in return flows. This reduced return flow scenario was created by adjusting inflows and losses in the baseline scenario. The comparison of the results from the two scenarios enables quantification of the potential implications of reduced return flows in isolation of other factors. An analysis of reduced return flows on the catchment scale mass balance and the river flow regime is presented.

The results from this comparison of modelled scenarios will help inform discussion on the relative risks to environmental objectives associated with reductions in return flows. As better information about return flows comes forward, the model can be updated and re-run to ensure best available knowledge on the risks is available to policy and decision makers. The comparative scenario analysis process using Source allows the implications of reduced return flows in a complex water sharing system to be quantitatively assessed in a transparent and comprehensive manner.

Keywords: *Water sharing, return flows, Source modelling environment*

Using eWater Source for detailed site water balance modelling and assessment

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Abstract: Water balance models are beneficial to the understanding of hydrological and water quality site conditions and interactions with local receiving environments. Therefore, in this study we develop a linked catchment (Source Catchments) and water balance (Source Rivers) model to simulate water quantity (runoff volume) and quality (total suspended solids (TSS)) at the local (site) scale. The integrated site water balance model was applied to a portside development located in Australia.

The site covers an area of about 130 ha, including wharf and loading facilities, rail facilities, bulk materials storage and surface water storage and settling ponds, buildings, internal access roads and utilities. Surface runoff is managed by ground contouring and a water management system comprising table drains, pipe/pits, sumps, settling ponds and holding tanks for containment and reuse. Site processes include surface runoff generated by catchments and 'clean water' diversion to stormwater basins, sediment generation, collection of surface water at sumps, pumping from sumps to gravity collection system, pumping between basins and storage tanks, overflows from settling ponds, and the re-use of stormwater (process water) to satisfy site demands and as a means of dewatering storages. Tertiary stormwater from settling ponds is also transferred to holding tanks which are used to supplement onsite water demands.

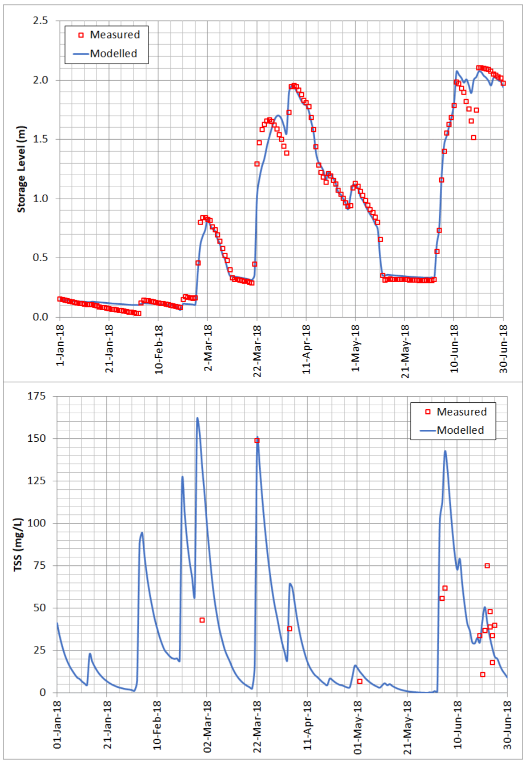

Figure 1. Water balance model calibration

A catchment model (24 sub-catchments and nine functional units) using SIMHYD was prepared to estimate runoff for the site. The balance of water was simulated using inputs (direct rainfall and runoff) and outputs (operational demands and evaporation) applied to each storage, and by accounting for overflows, pumping and other functional rules occurring between the storages. In total, the model incorporated 55 inflows (runoff and process water), 35 confluences, 43 storages (sumps and basins), 142 links and five supply point/water users to represent the water management system. The model was calibrated to observed water level and TSS data (Figure 1) to confirm that the model produced realistic estimates of runoff volume and TSS concentration.

The water management system was simulated continuously at daily intervals for both short-term (historical events) and long-term (multidecadal) periods. The model was used to investigate options to reduce potable water demands, maximise reuse of captured water and minimise discharge of sediment-laden water to offsite locations. The study highlighted that eWater Source can be successfully applied to simulate detailed water balances at the site scale. The water balance model provided an improved understanding of site water management conditions and a technical basis and justification for the short-listing of beneficial water management options. Importantly, the methodology developed here can be applied to other sites where the balance between stormwater, process water, demands, and off-site discharge is of interest.

Keywords: *Water balance, water quality, stormwater reuse, integrated modelling*

Using the Source Murray Model to calculate Annual Permitted Take under the Sustainable Diversion Limits in the Murray-Darling Basin Plan

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Abstract: The Murray-Darling Basin Plan (MDBP) requires states to manage diversions at or below the Sustainable Diversion Limit (SDL) determined for each SDL resource unit. Under the MDBP each SDL resource unit has a Baseline Diversion Limit (BDL) set. The BDL is an estimate of the average annual diversion able to occur over the climatic period 1895 to 2009 under the laws and policies that existed in the Murray-Darling Basin (MDB) as of June 2009. The SDL's are determined as the average annual diversion that can be extracted over the same climatic period while keeping the riverine environment healthy. To achieve the SDL's water has been recovered from consumptive uses in the MDB through a combination of market purchases and efficiency measures. The recovered water is to be used to achieve specified environmental outcomes.

The Source Murray Model (SMM) uses the Source modelling platform to represent both the hydrological behavior of the River Murray and Lower Darling Rivers, and the complex sharing and management rules that distribute this resource between the states of New South Wales, Victoria and South Australia. The SMM has been configured and used to calculate the BDL's for six SDL Resource units and has also been used to model Water Resource Plans (WRP's) which are configured to represent the water policies as of 2019 and generate average annual diversions are consistent with the SDL across the 1895 to 2009 climatic period.

Actual annual diversions in the River Murray will vary widely from year to year depending on such factors as resource availability and climate. If actual annual diversions were only compared to the SDL, the annual variability would mean that it would take a very long time to be confident that actual diversions were compliant with the SDL's. In order to ensure that SDL's are maintained under post July 2019 climatic conditions, the SMM will also be used to calculate the Annual Permitted Take (APT) each year. The APT will be undertaken by using the WRP configuration of the SMM with storage volumes, water account balances and other key model parameters set to 1st July 2019 values and using the latest water years observed rainfall, temperature, evaporation and runoff data. The use of the SMM for the APT should enable trends in growth in diversions to be detected earlier and with greater confidence, as well as checking behavior of individual years.

Keywords: *Source Modelling environment, Murray-Darling Basin Plan, Sustainable Diversion Limit*

EXTENDED ABSTRACT ONLY

Considerations in developing a modelling tool for Integrated Water Resource Assessment in Melbourne

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Abstract: In the past, Melbourne's water supply system sourced all of its water from the rivers and creeks in water supply catchments. Following a long drought that resulted in a severe depletion of water held in storage, the available supply sources have changed significantly over the past two decades. Recent additions to the supply sources include a sea-water desalination plant and the gradually increasing uptake of alternative water sources available in urban areas (stormwater, recycled water and rainwater). Despite a significant reduction in per capita water consumption in Melbourne, water demand from the system is increasing due to population growth. With no further surface water sources to harness, future increases in water demand and the reductions in catchment inflow due to climate change will need to be balanced with increased use of desalinated supplies and urban water sources.

The headworks system model assists with water resource planning and management. The use of urban water sources is currently represented in the model as a reduction of demand from the centralised supply system, but with no explicit representation. A new approach is being developed within the eWater Source platform to include water availability from urban areas. This will assist in better informing future water resource management decisions by considering a broad range of water sourcing options and their costs, benefits and consequences across the urban water cycle. The integrated representation of various components of the urban water cycle is being informed by data and models from internal and external stakeholders who have responsibilities in urban water cycle planning and management. The currently available set of modelling tools include those representing water supply headworks system behaviour, rainfall-runoff in water supply catchments and urban areas, urban demands and the sewer network.

The incorporation of available modelling tools (or the processes modelled by them) within an integrated assessment framework has presented many opportunities as well as challenges. The opportunities, in addition to those mentioned above, include the facilitation of strong stakeholder engagement and sharing of information. Challenges that need to be addressed include:

- developing a modular and scalable approach where specific components can also be adopted and used by stakeholders to meet their needs;
- facilitating linkages between modelling systems that are designed to meet specific needs and represent different spatial and temporal scales;
- future maintenance and update of a multidisciplinary modelling system;
- knowledge management and skill development across the broad areas represented by the modelling tool; and
- developing a model with the right trade-off between the complexity of the model, suitability for intended purposes and useability.

The first four of these challenges represent a paradigm shift from the previous modelling approach that covered one specific area of the urban water cycle, namely the centralised water supply headworks system.

The modelling tool is being developed incrementally for components of the water cycle to ensure the evolution of the modelling approach addresses the challenges outlined above. Specific components of the modelling tool and how the above challenges have been addressed will be presented.

Keywords: *Water resource modelling, alternative water sources, integrated assessment, urban water cycle modelling*

A vision for future hydrologic modelling to support Victoria's evolving water resource management

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Abstract: The development and management of Victoria's water resources has undergone major changes as the supply system was developed, entitlements and property rights were established and diversions grew. The growth of diversions, particularly within the Murray-Darling Basin, was not sustainable. These changes were major drivers of the process of water reform which was begun in 1994. The impact of the water reform on Victoria's water supply systems has been important and created many opportunities to sustainably manage water resources. These included a cap (or limit) on diversions, the separation of entitlements from land, the establishment of a water market, improved efficiency in water use and the recent Murray-Darling Basin Plan water recovery to better protect the environment. These water reforms have resulted in water supply systems becoming far more complex to manage, operate and meet compliance. For example, the local irrigation areas had a defined boundary prior to water reform. There was fixed number of licences attached to the land and allocations to those licences. Now, water that may once have been used for irrigation in one irrigation area may be traded and used for consumptive as well as non-consumptive purposes in other areas within a connected system or vice versa, for example the southern connected Murray-Darling Basin and Melbourne system.

As the regulatory framework has evolved over the past twenty-five years, so too has water demand patterns of all users. For irrigators, this has included adapting irrigation practices to manage their water entitlement usage, manage their risk and improve their water use efficiency. Victoria has also invested significantly in the modernisation of the irrigation distribution system itself to minimise distribution losses and recover water. Urban use has changed with improved water efficiencies and alternative sources of supply such as storm water, rainwater tanks and recycled water. New environmental entitlements have been created to deliver environmental outcomes. There are delivery capacity constraints to consider as competing water demand patterns change including both consumptive use as well as the large-scale delivery of environmental water.

Throughout the process of water reform, hydrologic modelling has been continuously developed to cope with real world changes and played a key role to inform policy and compliance framework. Moving forward, modern software tools and technology are required to meet water industry needs to model the system as it is now and may be in the future. Victoria contributed to the development of the National Hydrological Modelling Strategy (NHMS) to plan for its modelling requirements. The NHMS ensures that Australia's hydrologic modelling capability, community and software is ready to meet the priority hydrological modelling needs of Australian governments. Source is a modelling tool that has been developed within the NHMS. Victoria has implemented Source in many valleys including the foundational model of Goulburn, Broken, Campaspe, Coliban and Loddon system, and is developing Source models for other parts of Victoria.

Looking forward, there is a need and an opportunity for the hydrological models to be applied in a transparent, repeatable and defensible way for a wide range of applications with different purposes such as: (i) a planning model to support water management practices including assessing alternatives sources for urban water supply, catchment modelling of climate change and land use change, (ii) an operational model which may input live climate and streamflow data feeds for flow and demand forecasting, (iii) a tool for compliance which at a basin or state level requires modelling, (iv) environmental flow delivery, flooding issues, delivery capacity and salinity assessments, and (v) a planning as well operational tool to manage the movement of water through the water grid across the jurisdictions to meet competing water demand.

Source, a modern software, provides a platform for ongoing development and improvement to meet modelling needs across Australia. Challenges for future modelling, including representing complex interconnected systems, water trade, environmental requirements and accounting of water across all water users in a system with no boundaries and a continuously changing landscape. It is expected that the next generation of hydrological models, that leverage the Source software will provide a mechanism to explicitly or implicitly support analysis of a wide range of impacts of water management.

Keywords: *Hydrologic modelling, NHMS, water, Victoria, Source*

An iterative simulation-optimisation approach to catchment mitigation assessment using eWater Source

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Abstract: Cyanobacterial algal blooms within reservoirs can result in taste and odour issues in product drinking water. To address this, one option is to reduce the amount of phosphorus exported into reservoirs from their surrounding catchment, as it is often the limiting nutrient for algal growth. In order to assess the feasibility of catchment mitigation of phosphorus in the Mount Lofty Ranges for water aesthetic objectives, this paper presents a combined watershed modelling – optimisation approach to identify portfolios of grassy buffers, wetlands and sedimentation basins.

To support catchment mitigation planning in practice, this study demonstrated that iterative problem formulation, model development and use were required. In this iterative process, an eWater Source model, an emulation model, and genetic algorithms were developed to identify a number of mitigation portfolios that were compared and prioritised using trade-offs between cost, nutrient removal capacity and the number of measures included within the portfolio.

Optimisation was an important aspect of this assessment due to the difficulty of selecting a set of measures that could most efficiently reduce phosphorus export. These difficulties arise from the diffuse source of phosphorus, which flows to reservoirs along a number of different pathways, resulting in multiple locations at which phosphorus could be intercepted. Considering that each of these locations only intercepts a small proportion of the total phosphorus load, this means that a number of measures are generally required to have a sizable effect on phosphorus reduction. In addition, there are a number of different means to intercept phosphorus at each of these locations, which could be implemented at different sizes. In the problem addressed in this paper, 10^{70} different portfolios of adaptation options were feasible, which would have taken centuries of computational time to evaluate individually. The utility of the optimisation was that it effectively sifted through the multiple locations, measures and sizes that could form part of mitigation plans, in order to identify those combinations that worked best.

The value of the simulation-optimisation approach was that it helped provide insight into the decision problem, that would not have been possible using manual assessment processes. In this way, the process of using the optimisation was more important than the results obtained from it. The optimisation revealed (1) trade-offs between the amount of phosphorus intercepted and residence time based on the location of wetlands and sedimentation basins along stream networks, (2) how grassy buffers and wetlands/sedimentation basins work best in conjunction with each other, and (3) how the inclusion of buffers within optimal portfolios was very sensitive to assumptions regarding their effectiveness. It was these insights that helped develop a catchment mitigation plan.

Keywords: *Catchment management, water quality modelling, eWater Source, multi-objective optimisation, genetic algorithms*

Integrated urban water modelling for sustainable water management

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Abstract: Urban water managers are facing challenges to meet the increasing water demand arising from growing urban population. In addition to this, changing climate and increase in the frequency of extreme weather events have added an extra pressure. To cope with such challenges, sustainable water management is needed which can consider urban water cycle in an integrated manner. Such a development of sustainable water management in cities needs adapted modelling tools. Variety of models and sub-models are available. However, most of these models are limited to rural system and large basin scale. Further, the available models are either directed towards natural processes rather than urban hydrology or limited to local water recycle and reuse. The key to integration is to capture the overall water cycle components. Urban water cycle is interconnected with multiple sources available from household to city scale. Thus, an integrated urban water planning approach is required. Such approach not only model stormwater driven by rainfall-runoff process but also model water supply and wastewater system along with stormwater/wastewater treatment and reuse within the system that supports consumer's needs and demands. Hence, the integration of various sub models into integrated or coupled complex models is an urgent problem. This approach helps to identify the rainfall dependent and non-rainfall dependent supplies effectively and provides the opportunities that are not apparent when separate strategies are developed.

This paper demonstrates the development of an integrated model using a pilot case study with multiple supply scenarios. Three models namely, Source, MUSIC and Urban Developer are integrated for this purpose. Source is an integrated hydrological model applicable for river water planning, management and operation. MUSIC and Urban Developer can provide local scale treatment, reuse and recycle. Urban Developer model can assess multiple water service provision options at a range of scales from allotment through to the catchment. Combining of these three models offers an integrated modelling platform. The use of such comprehensive platform is very useful for water planners approaching towards integrated water management.

Keywords: *Integrated urban water modelling, Source, MUSIC, Urban Developer*

Applications of Source in the Australian Capital Territory

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Abstract: Canberra has a population of 425,000 people and is the largest urban centre in the Murray-Darling Basin. A range of water management challenges exist related to both water supply and water quality. Improvements in integrated water management modelling has been undertaken recently, with the development of a Source model for the ACT and region. This model consists of both a catchment model and a water resource model to support future planning scenarios and reporting requirements. A range of scenarios have already been developed, including current state, pre-development (assuming the state of waterways prior to European settlement), and a future urban development scenario. Future applications aim to incorporate aspects of both water supply and water quality, which will be calibrated by a waterway monitoring program developed specifically to inform model calibration. A project aiming to incorporate urban water demand is being scoped to enhance the Source model as a total water cycle model that addresses the specific needs of a growing urban environment in the face of climate change, reduced water availability and achieving long-term sustainability. As the largest urban centre in the Murray Darling Basin, urban domestic consumption is the primary form of water take. This is contract to elsewhere in the Basin, where agricultural abstraction is the primary consumptive user. Developing the capability to explore changes in urban demand and how this will impact upon the water cycle is a key challenge facing water managers in the Australian Capital Territory. Finally, implementation of the model within a data management system (Data Lake) coupled to a model version management system (GIT LFS) aims to ensure long term continuity of models through effective and transparent archiving of models, inputs and outputs, while providing a loosely coupled mechanism to regularly update data inputs to the model. This presentation will provide an overview of current projects spanning both the model development and integration, as well as applications of the model to inform policy and management activities.

Keywords: *Source, water management, version control, data management*

Calibration of flow model in a complex regulated river system in NSW, Australia

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Abstract: Surface water models, maintained by the NSW Department of Planning, Industry and Environment (DPIE), inform policy and decision making across NSW. These models are used to assess water availability, flows and diversions under varying climate conditions, as a critical step in informing the development of water sharing arrangements. Our models can be used for decades, for multiple purposes, often in ways unforeseen during initial development. Significant changes to modelling results, even improvements, can be problematic to stakeholders and must be managed carefully. However, we also need to provide confidence for communities and regulators that the modelling is based on the best available information and modelling practices.

The Department is developing several models on the eWater Source software platform, replacing the models previously built in the 1990s using IQQM. The new Source models will help facilitate inter-jurisdiction collaboration, and consistent analysis and policy development across the Murray Darling Basin, including the accreditation of water resource plans under the Basin Plan. These focused development efforts provide a unique opportunity to improve aspects of the model, such as flow calibration by using better data, more contemporary knowledge and rethinking our modelling techniques.

This study presents a case study of development of a full flow routing model using Source modelling platform in a highly complex regulated river system in NSW. The flow model was developed using a number of steps that included development of flow models in the headwater reaches and residual reaches first, which were then integrated to build a full flow model by stitching the stand-alone reach models together. The reach models use observed inflow to a reach, whereas, the stitched model uses simulated inflows for the entire system.

While the individual residual reaches were calibrated based on the period of observed flows defined by the upstream and downstream observed data, when combined into a single model, a common period of assessment was required. Based on available data from upstream inflow and historical water diversions, flow data for a suitable period was selected for the model calibration. A warm-up period of at least two years was used and sub-period evaluation of the model fit was undertaken to assess the performance.

The individual reach flow models were successfully calibrated, and the modelled flows reproduced the recorded daily flows reasonably well. The stitched model, combing all the individual reach models, was then assessed and evaluated by running the model without forcing the reach inflows to be the observed data. The results demonstrate that the full flow model successfully simulated the streamflow in the catchment. The calibrated full flow model is currently being used to build the other components (such as demand models and operational and management rules) to develop the full river system model.

Keywords: *Hydrological modelling, eWater Source, streamflow, NSW regulated rivers*

Afforestation impacts on streamflow generation in intermittent catchments

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Abstract: Land use is one of the key factors that controls streamflow generation in intermittent catchments. Modelling the response of intermittent catchments to disturbances such as land use change has received little attention. In intermittent catchments, surface runoff and subsurface flow might participate in the generation of streamflow but with different contributions during the periods of flow. Hence, because of discontinuities in the flow regime over a hydrological year, models should be able to reproduce not only flow rates and magnitudes, but also adequately represent subsurface water flow dynamics. Therefore, Integrated Surface-Subsurface Hydrological Models (ISSHMs) can be practical tools to account for heterogeneities of catchments, nonlinearities of rainfall-runoff responses, discontinuities in the flow regime, and interactions between surface and subsurface flow.

The goal of this study is to assess possible impacts of afforestation on streamflow characteristics in intermittent catchments using a series of land cover change scenarios. The ISSHM CATchment HYdrology (CATHY) was used to assess how different levels of afforestation in a catchment originally used as a pasture can affect the water balance of an experimental intermittent catchment in western Victoria, in the southeast of Australia. The scenarios include four different degrees of progressive (25%, 50%, 75%, and 100% of catchment area) conversion of pasture to a plantation. The area of pasture was increasingly reduced by 25% according to the topography, while the remainder of the catchment was kept unaffected; the conversion was implemented both from downstream to upstream and from upstream to downstream. The established plantation was assumed either to be mature from the beginning (static root water distribution with the plantation area instantly covered by trees with roots 6 m deep) or to grow over the course of a few years (dynamic root distribution with roots exponentially increased to 6 m during the simulation period).

As expected, afforestation was generally associated with a reduction in streamflow in the catchment; the reduction was more considerable when planting from downstream to upstream. Surprisingly, 25% and 50% pasture substitution with trees from downstream to upstream generated very similar streamflow. Because streamflow is mainly generated by the riparian area, the groundwater levels with these two different planted areas remained similar with little impact on flow. The simulations also showed the importance of the selected parametrization (i.e., static and dynamic roots) on the magnitude of the water budget. Evapotranspiration values in the static simulations were larger than the dynamic ones, resulting in the generation of lower amounts of streamflow.

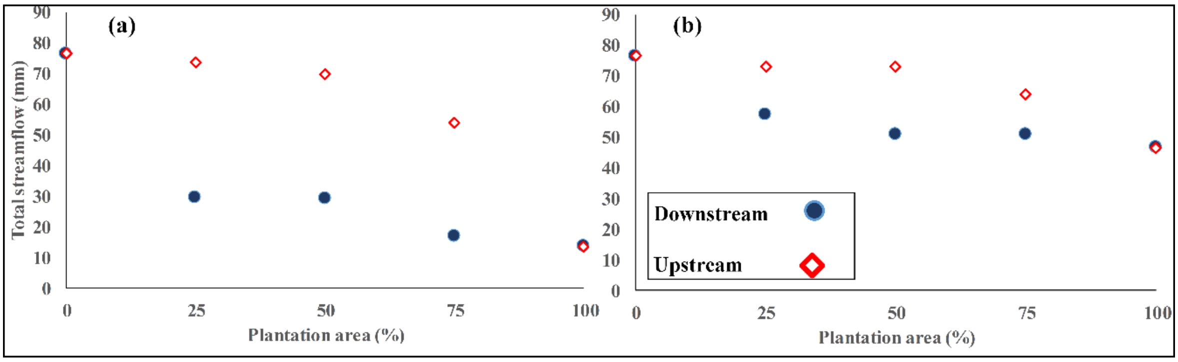

Figure 1. Total streamflow from 2013 to 2016 within the study area versus the plantation area, using (a) static and (b) dynamic root growth

Keywords: *Intermittent catchments, integrated surface-subsurface hydrological modelling, land use*

A simple ecohydrological model for estimating streamflow, evapotranspiration and gross primary production for Australian catchments

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Abstract: Streamflow (Q), evapotranspiration (ET), and gross primary production (GPP) are interrelated ecohydrological processes which are driven by energy to determine the water and carbon budgets of the land surface. Plants play as the vital media to regulate these processes. However, existing models either extensively or inadequately represent the coupled relationship between water and carbon as regulated by plant stomata, which limits their capability of evaluating climate change induced impacts on Q, ET and GPP. Here we propose an intermediate solution to estimate Q, ET and GPP simultaneously using a simple ecohydrological model. The model is based on a representative rainfall-runoff model (Xinanjiang hydrological model) to simulate Q, where the original 'water bucket' ET sub-model is replaced by a process-based ET and GPP model (PML_V2 model) to represent vegetation control of both water and carbon processes through bulk stomatal conductance. The model developed here is named as XAJ-PML_V2 model, which is capable of simulating Q, ET and GPP simultaneously and has only 12 free parameters. The model was tested against observed Q from 63 catchments and ET and GPP from 13 adjacent eddy covariance flux sites across Australia. Result shown in Figure 1 demonstrates that the simulated Q is in good agreement with the observed Q across 63 catchments, with average value of Nash-Sutcliffe Efficiency and coefficient of determination of 0.64 and 0.68, respectively. Simulations of ET and GPP at catchment scale are also comparable to the observations from their adjacent flux sites, despite the large spatial discrepancy between observation over catchment and flux site scale. The model was further used to investigate the impact of enhanced atmospheric CO_2 concentration (C_a) based on model experiments (Table 1). Using simulations of Q, ET and GPP under C_a=380 ppm as baseline, when C_a is prescribed to increase by 45% (550 ppm), simulated Q is increased by 12%, which is 3 times the simulated decrease in ET (4%) on average. Overall, the model is simple in structure and has few parameters, thus have the potential to be used for Q, ET and GPP estimation for other catchments located within and outside Australia. The model can also be implemented to investigating CO_2 induced variations in these key ecohydrological processes via plant biophysical response. This study demonstrates the importance of incorporating plant physiological response under a changing climate in simulating water (Q and ET) and carbon (GPP) processes. Further study is required to better constrain ET and GPP simulation and incorporate physiological feedback under elevated CO_2.

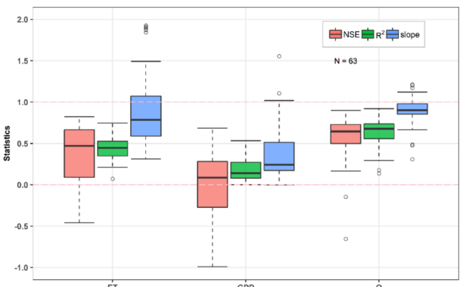

Figure 1. Summary of XAJ-PML_V2 model performance for streamflow (Q), evapotranspiration (ET), and gross primary production (GPP) across 63 (N) Australian catchments. The model was calibrated against observed daily Q at the catchment scale only. Simulated ET and GPP were compared with observed ET and GPP from adjacent eddy covariance flux sites near these catchments. Nash-Sutcliffe Efficiency (NSE), coefficient of determination (R^2), and linear regression slope (slope) are shown across 63 catchments. The solid line in each box represents the median value, whiskers are the 5th and 95th percentiles, open circles represents outliers. The 25th and 75th percentiles are shown as the lower and upper boundaries of each box.

Table 1. Summary of variation in catchment Q, ET, and GPP simulations under 45% increase in atmospheric CO_2 concentration (grouped according to flux site). Positive and negative values denote increase and decrease, respectively. 63 catchments grouped by their adjacent flux site.

site	Ade	DaP	DaS	Dry	Fog	Gin	How	RDF	Rig	Tum	Wac	Whr	Wom	**Mean**
PFT	SAV	GRA	SAV	SAV	WET	WSA	WSA	WSA	GRA	EBF	EBF	EBF	EBF	
ΔGPP (%)	22.16	19.24	19.24	22.03	21.06	**33.16**	22.97	19.24	23.28	24.43	21.63	26.49	24.33	**+23%**
ΔET (%)	-5.58	-6.22	-6.22	-0.93	**-7.09**	1.74	-6.16	-6.22	-1.90	-2.03	-2.04	-1.35	-2.21	**-4%**
ΔQ (%)	9.65	13.05	13.05	14.15	9.63	12.92	7.91	13.05	11.77	13.18	9.05	10.29	**17.49**	**+12%**

Keywords: *Streamflow, evapotranspiration, gross primary production, anthropogenic climate change, eCO₂*

Identifying flexible decision intervals for long-term operation of hydro-photovoltaic hybrid power system

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Abstract: Joint operation of renewable energy systems is becoming a trend in the hybrid power system management, and a major difficulty in the joint operation is the uncertain single optimal decision caused by the multiple energy forecast uncertainties. Since in the real-world operation, there exists many uncertainties and the optimal decisions are generally hard to perfectly conduct, the decision flexibility is desired for improving the long-term operation guidance. This study aims to identify a flexible decision interval, where the minimum power generation is still within an acceptable range, compared with the maximum system power generation. First, multiple forecast scenarios of the streamflow and PV output are generated as the ensembled forecast. Second, the deterministic optimization model for each scenario is developed. Finally, a double-layered model is used to identify the flexible decision interval and the Monte Carlo simulation is used to test the flexible decision interval. Results for a case study using China's Longyangxia hydro-photovoltaic hybrid power system indicate that the proposed method can identify multiple decision intervals with different levels of acceptable power loss. It is also found that the average width of the flexible decision interval increases with the acceptable loss for the hydropower generation. Thus, the proposed method could improve the decision flexibility for the long-term operation for the hydro-photovoltaic hybrid power system, with the acceptable loss of power generation loss. The use of flexible interval contributes to improving the long-term performance of hybrid hydro-photovoltaic power system, which is involved in multiple uncertainties caused by the human activities and climate change.

Keywords: *Hybrid power system, flexibility, joint operation, optimal design, Longyangxia hydro-photovoltaic hybrid power system*

Assessing the steady state assumption of catchment water balance

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Abstract: In computational yield hydrology, it is generally assumed that over a sufficient long period of time, changes in catchment water storage (ΔS) is a relatively minor term compared to flux variables and thus can be neglected in the catchment water balance equation. This has long been a fundamental assumption in numerous hydrological studies, such as the determination of long-term catchment evapotranspiration and the underlying basis of the Budyko framework. However, the validity of this fundamental assumption has never been comprehensively tested and the associated uncertainties in the water balance calculation remain unknown. In this study, we collect long-term (1982-2011) observations of streamflow and precipitation in 1057 global unimpaired catchments, in combination with multiple independent global evapotranspiration estimates to provide the first comprehensive assessment of the steady state assumption (i.e., ΔS approaches zero) in catchment water balance calculation. Two key scientific questions are addressed: (1) how long it requires for a catchment to reach steady state (T_{steady}) and its controlling factors; and (2) what is the error caused by the assumption in the water balance calculation (e_{wb}). Results show that when the threshold for steady state is 10% of the minimal fluxes (i.e., ΔS is smaller than 10% of the minimal of mean monthly precipitation, evapotranspiration and runoff), only about half of the catchments can reach steady state within 15 years and there are 248 catchments (~23%) fail to reach steady state within 30 years. Additionally, T_{steady} shows a significant positive relationship with climate aridity and negative relationship with vegetation coverage, with arid/semi-arid and low vegetation coverage catchments generally requiring a longer period to be stable. Other factors, including catchment size, elevation, slope, and soil properties are found to not affect T_{steady}. Averaged over all 1057 catchment, a minimal of 8 years is required for the steady state assumption to be valid, with humid catchments requiring 4 years and arid catchments requiring >30 years. Error caused by steady state assumption increases with the decreasing time for water balance calculation. For a typical 5-year mean, e_{wb} accounts for ~3.7% of P in humid catchments and increases to ~9.2% of P in arid catchments. Our results suggest that the steady state assumption in water balance calculation should be applied with consideration of the catchment's properties and climate conditions and call for caution when ignoring ΔS in arid and semiarid regions.

Keywords: *Catchment water balance, steady state assumption, storage change, error analysis*

Impact of root zone storage capacity on the streamflow anomaly in six catchments experienced tree die-off

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Abstract: It is widely recognized that forest reduction will lead to significant increase in catchment streamflow. Recently, six catchments in the western North America has experienced widely forest reduction (up to 86%) caused by bark beetle epidemics. However, expected streamflow increase resulted from forest reduction has not been supported by observations in the six catchments (four catchment runoff ratios of them decreased, and two of them increased non-significant). A few studies have attributed the anomaly to the increased transpiration by surviving and newborn vegetation from the perspective of increased carbon uptake. In addition to the change of transpiration, root zone storage capacity is recognized to be changed after the forest reduction. Root zone storage capacity is a core component of hydrology directly controlling hydrological response and transpiration process. While, few studies have interpreted the anomaly from the perspective of root zone storage capacity for lack of observation. Here, six catchments of North America that have experienced bark beetle epidemics are selected as the study catchments to study the impact of root zone storage capacity on the anomaly. The runoff ratio ranges from 0.39 to 0.56 before forest reduction. After forest reduction, the runoff ratio ranges from 0.32 to 0.61. The runoff ratios have both increase and decrease. A climatic method, without no direct observation of root, for estimating root zone storage capacity is employed. Results show root zone storage capacity of all the six catchments has increased ranging from 33 mm to 381 mm after bark beetle epidemics. A significant negative correlation is detected between the changes of runoff ratio before and after the bark beetle epidemic and normalized changes of root zone storage capacity before and after the bark beetle epidemic (R^2 = 0.64). The negative relationship suggests that increase in root zone storage capacity is the key driver of hydrological behaviors to induce no expected significant increase of catchment streamflow. This study demonstrates the increase of root zone storage capacity contribute to the decrease of streamflow. The larger root zone storage capacity can lead to larger initial rainfall loss during in dry days and result in smaller runoff coefficient. Maybe the impact of the increase of root zone storage capacity mitigate the expected significant increase of streamflow, even make the streamflow decrease. The results reveal the development of root zone storage capacity in the catchments with widely forest reduction induced by beetle epidemic and provide a better understanding for role of root zone storage capacity on the streamflow resilience.

Keywords: *Root zone storage capacity, streamflow increase, tree die-off, bark beetle epidemics*

The impact of vegetation change on global terrestrial runoff within the Budyko framework

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Abstract: In recent years, with the intensification of climate change and human activities, the global hydrological cycle is undergoing unprecedented changes. In particular, the impacts of vegetation change on hydrological cycle have attracted widespread scientific attention internationally. While such impact in different regions of the globe has been extensively investigated, a comprehensive understanding across the entire globe remains elusive. In this study, the relationship between vegetation change and runoff change at the mean annual scale across global catchments is investigated using the coupled water-energy theory. In addition, changes in global runoff due to changes in vegetation cover and climate over the past three decades is analysed.

Based on hydrometeorological observations of 676 unimpaired global catchments and satellite-derived leaf area index (*LAI*), we develop an empirical relationship between temporal changes in the Budyko's surface parameter *n* and *LAI*. It is found that the sensitivity of *n* to changes in *LAI* is positively correlated with climate dryness and negatively correlated with soil water holding capacity. With this and in combination with the Budyko model, an analytical framework of attributing runoff at the mean annual scale is developed. The developed framework is then applied at the grid-box scale (1º×1º) to attribute changes in global runoff during 1982-2014. Results show that the influence of vegetation change on runoff exceeds that of climate change in the arid, semi-arid and sub-humid environments. In humid regions, climate change, in particular change in precipitation, dominates changes in runoff. The influence of vegetation change on runoff shows a decreasing trend as climate becomes wetter, while climate change becomes increasingly important in the control of runoff change in more humid areas.

In summary, at the global scale, changes in runoff in the past three decades are mainly caused by vegetation change, while climate change only plays a secondary role, especially in relatively dry regions. Our results highlight the importance of vegetation change in the control of surface hydrological partitioning and call for attentions on developing appropriate vegetation management policies to better inform water resources management under the context of global change.

Keywords: *Vegetation change, hydrological cycle, Budyko, runoff change, climate dryness*

Understanding hydrological processes at a remote mountainous continuous permafrost watershed in a changing environment

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Abstract: This research assesses the possibility of using unique special observations data at the Suntar-Hayata station in Eastern Siberia (it was operating from 1957-1959 under the program of the International Geophysical Year) to develop and apply methods for modelling hydrological processes in the permafrost zone under conditions of poor information content to identify flow changes and understand the causes of their occurrence.

In the course of the work, the results of special observations were analysed, the parameters of the hydrological model, Hydrograph, characterizing the landscapes of the Eastern Siberia, were developed. The parameters were verified in the modelling of state variables at the Suntar River basin (7680 km^2) and the modelled streamflow compared with the observed values (1957-1964). The results of the simulation were found to be satisfactory. At the next stage, the water balance and hydrographs were simulated for watersheds over the period 1966-2012. The results of the simulation are satisfactory too. It allows us to conclude that the Hydrograph model can reproduce the processes occurring in the catchment area allowing it to be used in the flow modelling of the study area.

To study the possibility of modeling the observed flow changes, the flow simulation for the period 1966-2012 was carried out. Significant increasing trends in simulated runoff were seen in May - 11.3 mm or 118%, in September - 10.2 mm or 38.1%, in October - 1.3 mm or 33.3% and in November - 0.35 mm or 35.9%. These trends are comparable to trends seen in the observed flow values.

The simulation confirmed the theory that runoff changes are due to an increase in the proportion of liquid precipitation during the transition months. The liquid precipitation increased by an average of 13.6 mm for the Suntar River basin, which is similar to to the observed streamflow value trend in September of about 10 mm. Thus, the use of modelling methods can be a reliable tool for predicting runoff changes in permafrost. The method can be used to study the causes of runoff and variable state changes in other basins in the permafrost environment.

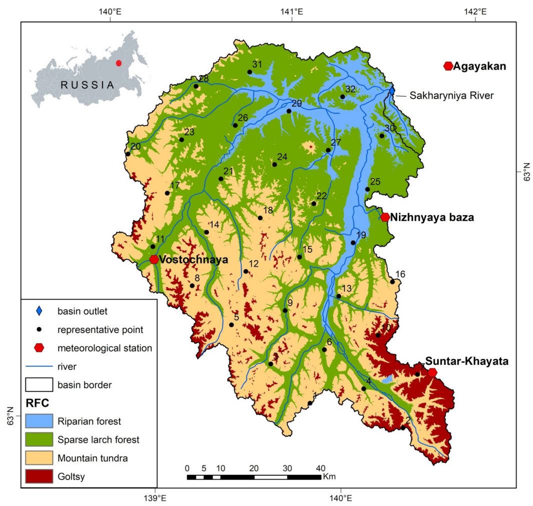

Figure 1. The Suntar River basin

Keywords: *Hydrograph model, parametrization, runoff formation processes, precipitation, climate change*

Comparison of two potential evaporation models on land

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Abstract: Potential evaporation is defined as the amount of water which would evaporate from a surface unconstrained by water availability. It has been widely used in meteorology, hydrology, agriculture, ecology and related fields. However, existing models for calculating potential evaporation have some long-standing problems in practical applications. First, the meteorological variables used in these models are not equivalent to the meteorological variables that should be used if the underlying surface is not water limited. Therefore, the calculated potential evaporation does not conform to the underlying assumptions of these models. Second, net radiation (R_n) and the surface temperature (T_s) are considered to be independent external forcings that determine the evaporation rate in the models. However, neither R_n nor T_s are independent of evaporation in practice, since R_n directly depends on T_s via the outgoing long-wave radiation.

To address these issues, Yang and Roderick (2019) recently proposed a new theoretical model for calculating evaporation over wet surface. The idea is to use forcings that are independent of evaporation and wetness of the underlying surface. The Yang-Roderick model shows that as T_s increases, the evaporative fraction (LE/R_n) increases but the net radiation (R_n) decreases. This means that there must be a maximum evaporation rate naturally emerges from this trade-off. Additionally, the maximum evaporation corresponds extremely well with observed evaporation over global ocean surface, suggesting the potential of the Yang-Roderick model for estimating potential evaporation over land. Here we use the Yang-Roderick model to estimate potential evaporation over the global land surface and compare it with the classical Priestley-Taylor model.

Both the Yang-Roderick and Priestley-Taylor models are adopted to calculate potential evaporation at both the global and the local scales. Results indicate that potential evaporation calculated by the Yang-Roderick model (LE_m) is larger than that obtained by the Priestley-Taylor model (LE_{PT}) at the global scale. Further analyses show that LE_m and LE_{PT} are almost identical when the underlying surface is wet and the difference between LE_m and LE_{PT} is increasingly larger as the underlying surface becomes drier.

We further investigate the underlying causes for the above difference. The Priestley-Taylor model assumes an open water underlying surface for calculating potential evaporation. However, the underlying surface is often subjected to moisture limitation over land. The observed surface temperature under non-saturated conditions is often much higher than that if the underlying surface is wet. This leads to an underestimation of R_n and therefore underestimation of potential evaporation by the Priestley-Taylor model.

A more interesting finding is that the surface temperature calculated by the Yang-Roderick model is similar to the air temperature (slightly higher than the air temperature due to positive sensible heat over wet surface), which further confirms that the Yang-Roderick model can recover the wet conditions for calculating potential evaporation, regardless the actual wetness of the underlying surface.

Keywords: *Potential evaporation, net radiation, surface temperature, Yang-Roderick model, Priestley-Taylor model*

Atmospheric CO_2 fertilization slows down the east-ward movement of the 100th Meridian

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Abstract: The 100th meridian is a conceptual arid-humid divide in physical climate and landscape of the United States, which effectively divide continent into arid west and humid east. This arid-humid divide line has exerted a strong influence on human settlement and agriculture development. With ongoing climate warming, a recent study project that this arid–humid divide line will move towards east as in the coming century, suggesting an overall drying trend around the 100th meridian. However, this projected drying trend contradicts with observed vegetation greening and runoff increase over the past decades and in climate model projections for the coming century. Here we re-examine observed change of this arid–humid divide in terms of vegetation, land hydrology, hydro-climate over the past decades (i.e., NDVI: 1982-2015, runoff: 1961-2010) and projected changes in the coming century under a high emission scenario (RCP8.5). Our results show a persistent and widespread increase of vegetation greenness around the 100th meridian regions, and the effective arid-humid divide regarding vegetation greenness moved westward with a mean shift of 0.37 degree in longitude during 1982-2015. Moreover, we found that the area with an increase in annual runoff is about 2.4 times of that with decreased runoff around the 100th meridian regions over the past five decades. For future projections, the ensemble of CMIP5 models also projects an increase in both vegetation greenness and productivity, but slightly increase in climate aridity and decrease in surface runoff. By the end of this century, the mean eastward shift of the arid-humid divide is 2.1 degree and 1.3 degree in longitude in terms of climate aridity and runoff, respectively. Nevertheless, the eastward movement of the arid-humid divide is much slower (0.8 degree and 1.8 degree less for aridity index and surface runoff) when account for vegetation response to elevated atmospheric CO_2 concentration. Increased atmospheric CO_2 concentration reduces stomatal opening and increases vegetation water use efficiency, which results in an increase in vegetation productivity at little cost of water. Our findings imply that historical and future tendency towards drying, as characterized by aridity index and runoff, may be weaker and less extensive than previously thought, even reversed towards a more humid tendency from a vegetation perspective.

Keywords: *The100th meridian, climate change, NDVI, runoff, aridity index, CMIP5*

Hydrological responses to land use change in tropical Australia: A case study of the North Johnstone River catchment

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Abstract: Land use change is one of the dominating driving factors of watershed hydrological change; thus, hydrological responses to land use change need detailed assessment to ensure sustainable management of both water resources and natural ecosystems. The Soil and Water Assessment Tool (SWAT) model was validated and used to simulate the impact of land use change (deforestation, afforestation and urbanization) on the water balance in tropical eastern Australia (i.e. the North Johnstone River catchment). Four land use change scenarios, according to the present land use conditions and the possible future land use plans of the catchment, were used to assess the impacts of land use change on the North Johnstone River catchment. Results showed that the modified SWAT model was able to reproduce smoothed MODIS LAI with NSE ≥ 0.59, $R^2 \geq 0.70$, and $|PBIAS| \leq 3\%$, and to predict monthly streamflow well with NSE ≥ 0.93, $R^2 \geq 0.94$, and $|PBIAS| \leq 8.3\%$. Results indicated that land use change had a certain impact on all hydrological variables, of which the impact on surface runoff was the most significant at monthly and annual time scales. Absolute changes of surface runoff under land use change scenarios differed across months, with the most significant change around the wet season from December to May. It was found that urbanization would result in increased surface runoff and decreased lateral runoff and groundwater, with no significant change in total runoff, actual evapotranspiration and soil water. What's more, afforestation could decrease surface runoff, increase evapotranspiration and lead to slight changes in other hydrological variables. Results revealed that for forest-evergreen and range-grasses, the positive correlation between annual rainfall and surface runoff were much less than the correlation between annual rainfall and other runoff variables (total runoff, lateral runoff and groundwater). Moreover, forest-evergreen generally produced less total runoff than range-grasses and urban areas under the same rainfall, terrain slope and soil texture. Furthermore, urban areas generally produced more surface runoff and less lateral runoff and groundwater than forest-evergreen and range-grasses under the same climate condition. These results contribute to the development of adaptation strategies and future policy plans for sustainable water management in tropical eastern Australia.

Keywords: *MODIS LAI, land use change, SWAT model, tropical eastern Australia, runoff*

Drought induced non-stationary in rainfall-runoff relationship invalidates the role of control catchment at the Red Hill paired catchment experiment site

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Abstract: The paired catchment experiments are the most rigorous and effective way to quantify the effects of vegetation change on catchment water yields. Based on observations from this kind of experiments, fundamental theory and several methods for separating impacts of changes in climate and vegetation on catchment streamflow have been developed and/or validated, such as three widely used ones, i.e. paired-catchment method, time trend analysis method, sensitivity-based method. Essentially, these methods are independent and should yield consistent estimations on the impacts of vegetation changes on catchment streamflow. However, consistency in estimated impacts of afforestation on catchment water yields based on these three methods has not achieved in previous studies at the Red Hill paired experimental catchment site in the west of New South Wales, Australia, and reasons haven't been revealed yet. In this study, observation of both treated (Red Hill, afforestation) and control (Kileys Run, unchanged) catchments of this paired catchments from 1990-2015 are collected to investigate the inconsistence amongst the three methods. Results show that estimated impacts of afforestation on the streamflow of treated catchment (Red Hill) are still not consistent even using much longer observations than previous studies. Estimated contribution of afforestation to streamflow reduction are 20.1%, 96.8%, and 87.8% using paired catchment method, time trend analysis method and sensitivity-based method, respectively. Examination of the long-term monthly rainfall-runoff relationship of the control catchment (Kileys Run), which has been used only in the paired catchment method amongst these three methods, indicates that it is not stationary and is confirmed by 6 independent methods including Mann-Kendall test, Pettitt's change point detection method, double cumulative mass curve, flow duration curve, rainfall-runoff linear regression curve, and data assimilation method by combing Particle filter with a monthly hydrological model. That is to say rainfall-runoff relationship of the control catchment is changed during the pre- and post-calibration periods. Further analysis suggests that a 13-year prolonged drought, occurred in the Southeast of Australia during the 1997-2009 (also called Millennium Drought), has induced the non-stationary in rainfall-runoff relationship of the control catchment and has led to the inconsistence in estimated impacts of afforestation on streamflow of the treated catchment (i.e. Red Hill) amongst these three methods. By including the changes in rainfall-runoff relationship of the Kileys Run caused by prolong drought, afforestation has caused a mean annual streamflow reduction of 106.3% using the paired catchment method, which is much more comparable with estimated impacts using the other two methods than an estimation of 20.1%. This study reveals that inconsistence in previous studies on the impacts of afforestation on water yields at the Red Hill paired experiment site is due to non-stationarity in the control catchment induced by prolonged drought. It highlights that management of water supplies, demands and risks in the future will possibly became more difficult and challenging as anthropogenic climate change is expected to have more and frequent extremes and thus can undermine the basic assumption of stationarity in long-term historical data.

Keywords: *Non-stationarity, paired catchments, Red Hill, rain-fall runoff relationship*

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