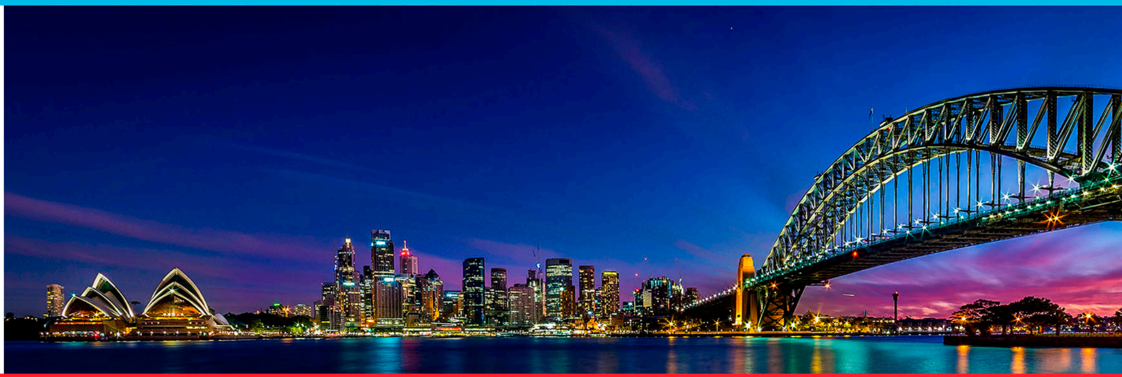
MODSIM 2021



SYDNEY, AUSTRALIA 5 – 10 December 2021

Modelling for action with a flood of data and a cloud of uncertainty

24th International Congress on Modelling and Simulation

Abstracts

EDITORS: Vervoort, R.W., Voinov, A.A., Evans, J.P. and Marshall, L.

Modelling & Simulation Society of Australia & New Zealand Inc.

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Defence Operations Research Symposium DORS MODSIM 2021 5 – 10 Dec 2021

iEMSs International Environmental Modelling & Software Society

International Microsimulation Association

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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 23 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 DSTG-led Defence Operations Research Symposium (DORS)

DSTG develops and utilises a broad range of OR methods and techniques to address current and future problems in Defence and to provide high impact advice to Defence. The focus is to contribute significantly to the development of future capability through supporting the evolution of joint concepts, future force structure, capability assessment, and opportunities to leverage disruptive technologies. By running DORS as an annual event, DSTG brings together the Defence OR community – including partners and collaborators from government, academia and industry – as an opportunity to highlight recent achievements in these areas and discuss current work. DORS therefore covers a range of topics applied across multiple domains (maritime, land, aerospace and joint) including the employment of simulation, optimisation, experimentation, wargaming and systems approaches.

About the International Environmental Modelling and Software Society

iEMSs is a not-for-profit organization uniting private persons and organizations dealing with environmental modelling, software and related topics.

The aims of the iEMSs are to: develop and use environmental modelling and software tools to advance the science and improve decision making with respect to resource and environmental issues. This places an emphasis on interdisciplinarity and the development of generic frameworks and methodologies which integrate models and software tools across issues, scales, disciplines and stakeholders with respect to resource and environmental issues; promote contacts among physical, social and natural scientists, economists and software developers from different countries and coordinate their activities; improve the cooperation between the sciences and decision makers/advisors on environmental matters; exchange information in the field of environmental modelling and software among scientific and educational organizations and private enterprises, as well as non-governmental organizations and governmental bodies. www.iemss.org

About the International Microsimulation Association

The International Microsimulation Association was founded in October 2005 with the aim of advancing the field of microsimulation. Microsimulation is a technique developed by Guy Orcutt which uses individual level data to model economic and social outcomes. The important detail is that all the modelling is done at the individual level, allowing the person doing the modelling to identify impacts of an external factor, like Government Policy, on individuals, families, households, firms, etc. These impacts can then be aggregated, and the impact on different sub-groups of the population (eg, age, income group, etc) can be identified. In the field, this is called identifying the distributional impacts. The paper outlining Orcutt's original vision is republished in the International Journal of Microsimulation. www.microsimulation.org

About the 24th International Congress on Modelling and Simulation (MODSIM2021)

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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3	September 1978	Australian National University, Canberra, ACT
4	August 1980	The University of Queensland, Brisbane, QLD
5	May 1982	The University of New England, Armidale, NSW
6	August 1984	Adelaide University, Adelaide, SA
7	May 1987	Royal Melbourne Institute of Technology, Melbourne, VIC
8	September 1989	Australian National University, Canberra, ACT
9	December 1991	Greenmount Resort Hotel, Gold Coast, QLD
10	December 1993	The University of Western Australia, Perth, WA
11	November 1995	The University of Newcastle, Newcastle, NSW
12	December 1997	University of Tasmania, Hobart, TAS
13	December 1999	University of Waikato, New Zealand
14	December 2001	Australian National University, Canberra, ACT
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
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21	December 2015	Gold Coast Convention and Exhibition Centre, Broadbeach, QLD
22	December 2017	The Hotel Grand Chancellor Hobart, TAS
23	December 2019	The National Convention Centre, Canberra, ACT

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Session organisers

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Distinguished Professor Belinda Medlyn

Western Sydney University

Climate change and Australian vegetation: Where are we headed?

Belinda Medlyn is Distinguished Professor of Ecosystem Modelling at the Hawkesbury Institute for the Environment, Western Sydney University. Her research focuses on modelling responses of plant ecosystems to environmental change, particularly rising carbon dioxide, warming temperatures, drought and heatwaves. She currently holds an Australian Research Council Georgina Sweet Laureate Fellowship and is leading a team developing a dynamic vegetation model that aims to predict future dynamics of Australian vegetation. She collaborates widely to synthesise experimental data and develop evidence-based models of climate impacts on vegetation. For example, her work on water use by plants drew together the main strands of evidence about stomatal behaviour to develop a unified theory that serves as a major framework for research in this area. She has been instrumental in international projects evaluating ecosystem models against Free-Air CO2 Enrichment (FACE) experiments, and leads model synthesis activities at the Eucalyptus FACE experiment in Western Sydney. Her work on modelling drought death in forests led her to establish the Dead Tree Detective citizen science initiative. She is an editor for New Phytologist, a member of the Terrestrial Ecosystems Research Network (TERN) Science Advisory Committee and a Clarivate Analytics Highly-Cited Researcher (2018-2020).

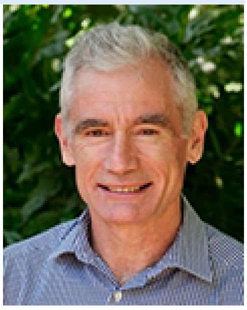
Professor Holger Maier

University of Adelaide

Unite and conquer: Overcoming decision paralysis and confusion in the face of a cloud of methods, models and metrics

Holger is Professor of Environmental Engineering at the University of Adelaide. His interests are in developing and applying methods that result in sustainable outcomes, especially when dealing with complex systems in an uncertain environment. Examples of this include the development of decision support systems for long-term disaster risk reduction under a range of plausible futures, the development of innovative bottom-up climate impact assessment methods, the development of adaptive approaches to urban stormwater management using smart technologies and the development of approaches supporting the decarbonisation of the gas industry. Holger is a Fellow of the Modelling and Simulation Society of Australia and New Zealand, a recipient of the Biennial Medal of the International Environmental Modelling and Simulation Society and an Editor of Environmental Modelling and Software.

Professor David Hamilton

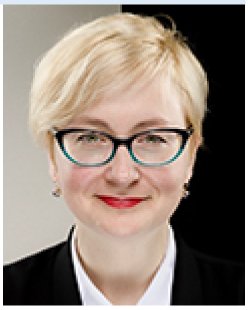


Australian Rivers Institute, Griffith University

Are our models keeping pace with the evolving data deluge?

David Hamilton is Deputy Director and Professor in Water Science at the Australian Rivers Institute, Griffith University. He has held positions bridging engineering and environmental sciences; in Environmental Engineering at the University of Western Australia, Biological Sciences at the University of Waikato in New Zealand, and his current position. He was the inaugural Bay of Plenty Regional Council Chair in Lake Restoration at the University of Waikato and held this position from 2002 to 2017. As Lake Restoration chair, he worked closely with lake managers to implement predictive models to support restoration programs. This work, along with a national-level lake restoration program, culminated in publication of The Lake Restoration Handbook: A New Zealand Perspective in 2019. Hamilton uses autonomous environmental sensors to improve model predictions that provide insights into the recovery of freshwater ecosystems. He has been closely involved in management and policy implementation for freshwater ecosystems, holding appointments with the Ministry for the Environment (NZ) and advisory roles for regional councils and industry groups in New Zealand and Australia, as well as supporting assessments in USA, Thailand, Austria, China, Western Samoa and Malaysia. He is a past President of the New Zealand Freshwater Sciences Society, editor-in-chief of the scientific journal Inland Waters and associate editor for several other aquatic journals.

Professor Ganna Pogrebna



The University of Sydney

Anthropomorphic learning: Bridging behavioural science and data science to predict human behaviour

Ganna Pogrebna is Professor of Behavioral Business Analytics and Data Science at the University of Sydney. She also serves as a Lead of Behavioral Data Science strand at the Alan Turing Institute – the national centre for AI and Data Science in London (UK), where Ganna is a fellow working on hybrid modelling approaches between behavioral science and data science (e.g., anthropomorphic learning). Ganna published many articles in high-quality peer-refereed journals. Prior to joining the Leadership Quarterly editorial team, Ganna served as an associate editor of Judgement and Decision Making journal. Ganna studied Economics at the University of Missouri Kansas City (US) and the University of Innsbruck (Austria). She holds a Ph.D. in Economics and Social Sciences. At different points of her career, Ganna worked at Columbia University in New York (USA), the University of Bonn (Germany), Humboldt-Universität zu Berlin (Germany), the University of Innsbruck (Austria), the University of Warwick (UK), and the University of Birmingham (UK).

Blending behavioral science, AI, computer science, data analytics, engineering, and business model innovation, Ganna helps leaders in businesses, charities, and public sector to better understand why they make decisions they make and how they can optimize their behavior to achieve higher profit, better social and commercial outcomes, as well as flourish and bolster wellbeing of their teams. Her recent projects focus on the role of smart technological and social systems, human-computer and human-data interactions, as well as human-machine teaming in organizations and how these current and future technologies impact leadership and leaders' decision making.

Ganna published extensively in high-quality peer-refereed journals including the Leadership Quarterly, Management Science, Economic Journal, Journal of Applied Econometrics as well as many others. Ganna's work on risk analytics and modelling was recognized by the Leverhulme Research Fellowship award. In January 2020, she was also named as the winner of TechWomen100 – the prize awarded to leading female experts in Science, Technology, Engineering and Mathematics in the UK. She is also named as one of 20+ Inspiring Data Scientists by the AI Time Journal. Over the years, she led as well as contributed to a large number of projects, funded by UK Research and Innovation (including ESRC, EPSRC, and other governmental bodies in the UK), the Leverhulme Trust, as well as a number of private organizations; and won competitions for over a total of £15 million in research funding since 2013.

Ganna runs the Data Driven blog on YouTube (https://bit.ly/datadrivenyoutube), cybersecurity blog CyberBitsEtc, as well as Inclusion AI blog. She is also an occasional contributor to the VOXEU blog, BBC blog, and the Alan Turing Institute blog. Her work is regularly covered by the traditional as well as social media. Ganna is one of the contributors to the Oxford Handbook of AI Ethics. She is also currently co-editing the Cambridge Handbook of Behavioral Data Science, which is due to be published in 2022.

Dr Matthew Adams

Queensland University of Technology
(President’s invited plenary for mid-career researchers)

Exploiting the exciting interface between mechanistic and statistical models

Matthew is a Lecturer of Applied Mathematics at Queensland University of Technology, Brisbane. He is an applied mathematical modeller of environmental and biological systems, with a strong interest in using these models to inform decision-making. Matthew's work aims to bridge the gaps between modellers and decision-makers, by showing how mathematics can be used to gain substantial insights into how environmental systems function as well as inform their management. Mathematical techniques of interest include differential equation models, Bayesian statistics, and value-of-information analysis, but ultimately the technique used depends on the goal of the research. He is currently contributing decision science support for the Great Barrier Reef's Restoration and Adaptation Program, using models to investigate the potential for catastrophic ecosystem shifts in Antarctica, and developing new communication tools to improve model-data integration in the water modelling sector. Matthew was the recipient of a Discovery Early Career Researcher Award in 2020.

Exploiting the exciting interface between mechanistic and statistical models

Matthew P. Adams [a,b]

[a] *School of Mathematical Sciences, ARC Centre of Excellence for Mathematical and Statistical Frontiers, and the Centre for Data Science, Queensland University of Technology, Brisbane QLD Australia*
[b] *School of Chemical Engineering, The University of Queensland, St Lucia QLD Australia*

Email: mp.adams@qut.edu.au

Abstract: When modelling real-world phenomena, there may be a flood (or a drought!) of data accompanied by a cloud of uncertainty. But where does this uncertainty come from? The uncertainty could be irreducible, and thus our best bet is to use the available data to devise a statistical model. We may, given time, be able to obtain process-based understanding of the system, and then our best bet might be to devise a (usually complicated!) mechanistic model.

However, the true pathway in many cases lies somewhere in between. This creates tension for mathematical modellers who may typically have been trained in one of two camps: (1) a process-based world that hinges on a physical understanding of the system, represented by some combination of ordinary differential equations, partial differential equations, and other physical formulas, or (2) a world built on correlations or formulas with little physical underpinnings but provide a solid foundation to produce meaningful predictions quickly. Research in the latter camp has exploded recently with the expansion of machine learning and artificial intelligence techniques, but is also beginning to introduce regulations that ensure quality control in the application of these techniques (e.g. responsible artificial intelligence). Mechanistic and statistical models can learn much from each other. For example, process-based models can be used to sense-check the predictions of statistical models, and statistical models can emulate process-based models for rapid gains in computational efficiency. Strategic model hybridization from these two different approaches may yield a balance between mechanistic insights and impactful outcomes.

This talk explores research work which bridges the divide between mechanistic and statistical models. Such work typically requiring cross-training at the postgraduate or postdoctoral level and is a potential route to take best advantage of the strengths of both modelling strategies. Analogous to the broader tension felt between fundamental and applied research, hybrid modelling strategies may also have the potential to balance the two scientific progress goals of mechanistic insights and practical predictions. I will present some of the lessons my colleagues and I have learned about navigating this mechanistic/statistical interface with examples of surprising and unexpected outcomes we have seen in the fields of biology, ecology, agriculture and elsewhere. These examples include applications where:

- Statistical techniques can inform strategic simplification of mechanistic models,
- Mechanistic and statistical models have equal predictive power, but each has a preferred usage depending on the model's goal,
- Emulation of a mechanistic model will be utterly essential to practically inform decision-making, and
- Statistical assumptions vastly alter conclusions about parameter identifiability in both model types.

Keywords: *Mechanistic models, modelling approaches, predictions, scientific impact, statistical models*

Are our models keeping pace with the evolving data deluge?

David P. Hamilton

Australian Rivers Institute, Griffith University, Nathan, 4111, Australia
Email: david.p.hamilton@griffith.edu.au

Abstract: Environmental sensors collect information on a broad suite of variables at a range of spatial and temporal scales. At one extreme are remote sensing devices on satellites that provide information at regular intervals (days) over scales of tens to hundreds of metres. At the other extreme are in situ sensors that collect data from a fixed point at intervals of seconds to minutes. The integration and harmonisation of these data (see O'Grady et al. 2021) provide an unprecedented opportunity to test the predictive capability of process based models. The question arises: are we fully utilising this opportunity to improve our water models?

High frequency data can greatly increase the number of measurements available for comparison with state variable outputs from dynamic models, as well as supporting determination of kinetic parameters from rates of change of variables. For example, high frequency measurements of dissolved oxygen in water can be compared directly to modelled dissolved oxygen or used to derive indices like lake metabolism, as well being useful for quantifying key kinetic parameters like production and respiration. Variables such as temperature and dissolved oxygen, with appropriate quality control/quality assurance, are highly suitable for these types of assessments. Some variables measured with sensors (e.g., turbidity, chlorophyll fluorescence) require careful and skilled interpretation because they may only be proxies for model state variables and are often subject to a number of interferences. For this reason, sensors require user expertise through a full sequence of probe selection, deployment, calibration and quality assurance/quality control (QA/QC).

I contend that for a number of reasons, modellers have not yet exploited the potential of sensor data for model calibration and validation. First, compensation for sensor interference is often inadequate and readings can be misinterpreted; QA/QC of data is critical. Second, comparisons of measurements against model state variables remain the 'standard' for calibrating models. This option may be suitable for sparse, non-sensor data but it negates opportunities for direct calculation of kinetic parameters from, for example, using first and second time derivatives of sensor data (i.e., to identify rates of change and inflection points, respectively). Third, working with sensor data requires strong disciplinary expertise – similar to working with numerical models – and we need to break the disciplinary shackles to harmonise data and develop data assimilation techniques to drive model simulations and align measured proxies with state variables in models.

For calibration of water quality models, we often still rely on routine water sampling (e.g., collecting 'grab samples') at a measurement frequency that is orders of magnitude less than that used for sensors. This problem is relevant to many of the water quality issues that interest managers, e.g., whether an algal bloom will appear; the level of water contamination by pathogens; and whether nutrient levels are high enough to trigger water quality problems (e.g., deoxygenation of bottom waters). However, a new generation of smart field sensors that uses optical chemical and biosensors, automated eDNA methods and miniaturised laboratory instruments is beginning to address the issue of disparity of monitoring frequency for biogeochemical constituents that is relevant to models. Integration of data from these sensors into well-established sensor networks should enable the development of a new generation of biogeochemical algorithms for water models and allow us to progress beyond the lumped state variable approaches and Michaelis-Menten kinetics descriptions that characterise most current applications. With these advances, we will be in a better position to apply process based models to address the specific questions of relevance to water managers and narrow the confidence intervals of model projections.

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Keywords: *Remote sensing, high frequency sensor, data harmonisation*

Unite and conquer: Overcoming decision paralysis and confusion in the face of a cloud of methods, models and metrics

H.R. Maier

[a] *School of Civil, Environmental and Mining Engineering, University of Adelaide, Australia*
Email: holger.maier@adelaide.edu.au

Abstract: Research output is increasing at an ever-increasing pace. At the same time, there is a growing recognition of the need for this research by industry, who struggle to deal with mounting complexity and uncertainty. However, often, research outputs add to this complexity and uncertainty, rather than help alleviate it. This is partly due to the significant increase in the volume and availability of research outputs, but also because of the propensity of researchers to name, brand and market the methods, models and metrics they publish, without sufficient connection to each other and existing work. This makes it difficult for industry, and other researchers, to know which methods, models and metrics are most appropriate, as they are often viewed as competing, stand-alone alternatives. However, in many cases, these branded methods, models and metrics are strongly related to each other, as well as to those proposed previously (often many decades prior). Consequently, there is a need to articulate these connections and relationships to assist with overcoming the decision paralysis and confusion stemming from the naming, branding and marketing of methods, models and metrics, which fosters the illusion that users have to choose from one of a large number of competing paradigms, rather than from variations on a theme. This talk will present a number of examples of unifying frameworks in the areas of robustness analysis, uncertainty and sensitivity analysis, machine learning, optimisation and water resources management that highlight that many named methods, models and metrics are complementary, rather than competing paradigms. It will also challenge the research community to move away from the practice of naming, branding and marketing their "new" methods, models and metrics, and to clearly articulate the relationship with other, often historical approaches. Unfortunately, this is not encouraged by the metrics that are used increasingly to measure research performance, as they reward practices that favour competition, rather than collaboration, and encourage referencing research from recent years.

Keywords: *Modelling approaches, branding, unifying frameworks*

Climate change and Australian vegetation: where are we headed?

B.E. Medlyn

[a] *Hawkesbury Institute for the Environment, Western Sydney University, NSW, Australia*
Email: B.Medlyn@westernsydney.edu.au

Abstract: From the wet tropical rainforest to the saltbush plains, the Australian vegetation has been shaped by climate over millennia. Now, as anthropogenic climate change accelerates, we are likely to see significant impacts on the function and distribution of native vegetation, but it is not yet clear what form those impacts will take. Detection, attribution, and prediction of changes in vegetation remains a large challenge, particularly in Australia. Notable shifts that have been reported to date include: significant greening in some regions, likely associated with CO2 fertilisation; shifts in timing of pasture grass productivity, associated with changing rainfall patterns; tree dieback, associated with hotter droughts and pest outbreaks; and increased fire frequency, associated with increases in fire weather. Such changes in vegetation function have major implications for our land-based natural capital, and there is a critical need for predictive models to assess risks to ecosystem services.

A key challenge for prediction is to capture the interactions and feedbacks among environmental drivers (e.g. rising CO2 concentrations, increasing temperatures, changes to rainfall patterns) and vegetation processes (e.g. productivity, carbon sequestration, water use, nutrient cycling, flammability). Mechanistic vegetation models simulate the interactions among these major processes, and their responses to environmental drivers, in order to predict vegetation growth and dynamics over time.

Typically, however, there is significant disagreement across models, reflecting the considerable scientific uncertainty involved in attempting to describe and quantify the key biological processes. The use of model intercomparisons to identify major areas of disagreement and target experimental design to reduce uncertainty has proved to be a valuable way forwards, providing new scientific insight as well as improved confidence in model predictions.

One notable example of this approach has been the iterative application of vegetation models to Free-Air CO2 Enrichment (FACE) experiments. These experiments fumigate patches of vegetation to elevate atmospheric carbon dioxide (eCO2) and track changes in ecosystem processes over time. Several large-scale FACE experiments commenced in the late 1990's and ran for over a decade. The experimental data were then used to evaluate the responses to eCO2 predicted by a range of vegetation models. The data were able to discriminate among some sets of model assumptions – for example those related to water-use efficiency, carbon allocation, and tissue stoichiometry – but were not sufficient to constrain other model assumptions. Thus, for new FACE experiments, there has been a concerted effort to run model intercomparisons in advance of the experiment. At the Eucalyptus FACE experiment (EucFACE) experiment in western Sydney, for example, model intercomparison was used to identify a priori the major competing hypotheses causing disagreement among models, enabling data collection to be targeted at discriminating among these assumptions. Data emerging from the first five years of the experiment's operation are now being used to constrain and develop the next generation of vegetation models.

Similar approaches are being applied to advance model representations of processes leading to drought mortality, fire frequency, and vegetation distributions. The iterative model-data integration approach described here is a powerful way to advance scientific understanding and our capacity to predict, and plan for, future vegetation dynamics.

Keywords: *Dynamic vegetation model, carbon sequestration, carbon dioxide, climate change, model intercomparison*

Anthropomorphic learning: Bridging behavioural science and data science to predict human behaviour

Ganna Pogrebna

Discipline of Business Analytics, University of Sydney Business School, University of Sydney, NSW, Australia
Email: ganna.pogrebna@sydney.edu.au

Abstract: Understanding and modelling human behaviour is one of the major tasks facing industry and academia of the future. This task is especially important when we consider interactions between humans and technology. Decision support systems, suggestion systems, automation, etc. – all these technologically intense aspects of human life require accurate predictions of what people like, what people prefer, and where people need help of algorithms and automated agents. Under these circumstances, recent advances in computer science, statistics, and mathematics offer several methods which try to model human behaviour. Specifically, the methodology of machine learning and, more recently, deep learning allows us to generate predictions useful for many different facets of human life. Yet, there are many aspects of human life and decision making where machine learning and deep learning fail to provide reliable and accurate results. One of the most notorious examples is suggestion systems: many of us regularly shop online using different platforms (such as Amazon) and receive suggestions for future purchases. Yet, very few of us find these suggestions helpful. One of the reasons why AI fails in many cases to correctly anticipate human behaviour is that AI algorithms tend to ignore existing insights from decision theory and behavioural science.

By combining behavioural science models with AI algorithms, we are able to significantly improve and simplify predictions of human behaviour in a wide variety of contexts. The resulting methodology which we label *anthropomorphic learning* allows us to develop more functional systems which better understand humans. This methodology is explainable, traceable, requires smaller training sets and, generally, outperforms existing algorithms by generating more accurate predictions.

Anthropomorphic learning is one of the methods of *behavioural data science*, a new interdisciplinary field, which emerges as a direct response to the need for studying behaviour "in the wild", outside the "sterile" laboratory setting and controlled environments. The field's ambition is to identify ways to embed human values into the heart and operation of AI systems, establishing methods to verify their integrity, accountability, and resilience thereby ensuring that they, and the data which feeds them, ultimately operate in the service of successful, democratic, digitally empowered yet human-centred communities. This can only be achieved through rigorous, problem-oriented research, which goes hand-in-hand with practice.

Keywords: *Machine learning, deep learning, anthropomorphic learning, behavioural data science*

Multi-way correspondence analysis approach to examine Nobel Prize data from 1901 to 2018

T. Alhuzali[a], **E. J. Beh**[a] **and E.Stojanovski**[a]

[a]*School of Information and Physical Sciences, University of Newcastle*
Email: TurkiAbdulrahmanT.Alhuzali@uon.edu.au

Abstract: This study examines Nobel Prize data by studying the association between the nationality of the laureate, the discipline in which the Nobel Prize was awarded, and the gender of the recipient by maintaining the multi-way structure of the data. A three-way contingency table is formed by simultaneously cross-classifying the three categorical variables using a three-way correspondence analysis to assess the association between the three variables. The significance of this study lies in preserving the multivariate associations, which the multiple correspondence analysis approach does not allow. The multi-way correspondence analysis (MWCA) maintains all three-way associations as well as the pair-wise structures between the variables in the case of three variables. The present study consists of 785 individuals from eight developed countries that received a Nobel Prize in the period from 1901 to 2018 (inclusive) – the countries being Canada, France, Germany, Italy, Japan, Russia, British Isles and the United States of America, while the disciplines in which the individuals were awarded the prize include chemistry, physics, physiology or medicine, literature, economics and peace. The results from the MWCA suggest that a strong symmetric association exists between the three variables, in addition, there is a statistically significant association between each pair-wise combination of the variables. The application shows that male physics recipients tend to be from Russia, Japan, and France while female recipients were more likely to be from Japan and France. Furthermore, the analysis highlights that the female medicine recipients are predominantly from the United States of America and the British Isles.

Keywords: *Multi-way correspondence analysis, symmetric, asymmetric, Nobel Prize*

The Use of Exponential Smoothing (ES), Holts and Winter (HW) and ARIMA Models in electricity Price Analysis

Yasir Alsaedi [a b] and **Gurudeo Anand Tularam** [b]

[a] *Department of Mathematics, Umm Al-Qura University, Makkah, Saudi Arabia,* [b] *Centre for Planetary Health and Food Security , Griffith University, Australia*

Email: yasir.alsaedi@griffithuni.edu.au

Abstract: Electricity pricing is among the most important contemporary policy issues facing Australia, and electricity prices represent a critical component of on-going discussions concerning energy and climate change policies. In fact, several attempts to move forward with such policies have been stymied by concerns about potential increases in electricity prices. One example of the crisis in action can be seen in the closure of the Hazelwood Power Station, which slashed Victoria's energy supply by 22%, causing annual energy bills to soar by an average of $300 per household. Therefore, energy analysts and government organizations alike require guidelines to help them choose the most appropriate forecasting techniques so that they can achieve accurate predictions of spot pricing trends.

The aim of the present study is to compare the application of the exponential smoothing (ES), Holt-Winters (HW), and autoregressive integrated moving average (ARIMA) forecasting methods in relation to spot electricity pricing. The assessment is made in the context of the Australian National Electricity Market (ANEM). In order to determine the most appropriate model, four different strategies are applied as selection criteria in order to quantify the accuracy of the model predictions, namely the mean squared error (MSE), root-mean-square error (RMSE), mean absolute error (MAE) and mean absolute percentage error (MAPE) strategies. The comparison indicates that the HW model performs better than the ES model in terms of its predictive power, with a confidence interval of 95%. However, the ARIMA (1, 1, 1) model yielded the best results, leading us to conclude that this sophisticated and robust model outperformed other simple yet flexible models in electricity market. This study will make two significant contributions to the current literature. First, it will help policymakers and industry marketing strategists to select the most appropriate forecasting method for the spot electricity market. Second, it will help traders to assess the appropriate position at over-the-counter and well-developed futures trading platforms (e.g., ASX), since the accurate forecasting of spot prices is important for derivatives pricing.

Keywords: *Spot electricity price, Forecasting, time series analysis*

Model-based clustering with mclust R package: Multivariate assessment of mathematics performance of students in Qatar

Ali Rashash R Alzahrani [a,b] **, Eric J. Beh** [a] **and Elizabeth Stojanovski**[a]

[a] *School of Information and Physical Sciences, University of Newcastle, Newcastle, Australia,* [b] *Mathematical Sciences Department, College of Applied Sciences, Umm Al-Qura University*
Email: alirashashr.alzahrani@uon.edu.au

Abstract: This study demonstrates how model-based clustering can be undertaken using `mclust`, a contributed R package, to examine factors influencing mathematics performance of high school students in Qatar. Although there are numerous cluster analysis approaches, this paper highlights the intricacies, assumptions, limitations, benefits and pitfalls of clustering using a model-based approach, and how the inherent inadequacies of other clustering approaches can be better explored using model-based methods. Moreover, this paper demonstrates how the `mclust` package can be used to concurrently analyse and compare different models, in order to select the preferred clustering model according to the Bayesian information criterion, and to estimate parameters of the associated model using maximum likelihood estimation. The benefit of selecting a prior to avoid model-based clustering estimation singularity- and degeneracy-related issues offers an alternative approach to improve the rate of convergence. The results from applying model-based clustering using `mclust` to educational data that examines the mathematics performance of secondary students in Qatar will be used to identify factors that influence mathematics performance for different clusters of students, to help facilitate potential adoptions of the most appropriate remedial teaching strategies to implement to enhance learning. Furthermore, the results can help teachers to identify groups of students whose performance in different subject areas is likely to be affected by certain factors, thereby helping them to reduce potentially undesirable learning outcomes.

Keywords: *Hierarchical clustering, mclust, Bayesian information criterion, Model-based clustering*

Robust detection of statistically significant correlations in geophysical timeseries: A Monte Carlo method accounting for serial dependence and sampling uncertainty

M.S. Armstrong[a], **A.S Kiem**[a] **and G. Kuczera**[b]

[a]*Centre for Water, Climate and Land, University of Newcastle, Australia*
[b]*School of Engineering, University of Newcastle, Australia*
Email: matthew.armstrong@uon.edu.au

Abstract: Two geophysical timeseries may share a common low-frequency signal that is distorted by high-frequency noise. As such, these timeseries are often filtered to remove the high-frequency noise prior to performing statistical analysis. However, this filtering artificially increases the serial dependence of the timeseries, meaning that the assumption of independent data underlying most standard correlation tests (e.g. Pearson's correlation) is violated. Monte Carlo methods that account for serial dependence when comparing serially dependent data are typically focused on either (a) calculating the p-value of the observed correlation with respect to an empirically derived null distribution, which is derived by calculating the correlation between independently generated replicates of the observed data or (b) estimating sampling uncertainty in the observed statistic by performing a block bootstrap, with block size proportional to the serial dependence in the timeseries. In this study, we present a Monte Carlo test that combines these two approaches and, in doing so, explicitly accounts for serial dependence and sampling uncertainty when comparing two timeseries. A case study is presented that demonstrates the ability of the proposed method to detect statistically insignificant correlations when performed on filtered white noise timeseries. Crucially, existing methods accounting for serial dependence detected a statistically significant, spurious correlation. This demonstrates that the proposed method is suitable for use when performing statistical analysis on filtered timeseries.

Keywords: *Monte Carlo, Bootstrap, Computational statistics*

Multipath measurements clustering of over-the-horizon radar based on affinity propagation

Xianglong Bai[1], **Zengfu Wang** [1], **Hua Lan** [1] **and Quan Pan** [1]

[1.] *School of Automation, Northwestern Polytechnical University, Key Laboratory of Information Fusion Technology, Ministry of Education, Xi'an 710129, China*
Email: baixianglong@mail.nwpu.edu.cn

Abstract: The multi-layer structure of the ionosphere can support several signal propagation paths between the sky-wave over-the-horizon radar (OTHR) and targets, and often giving rise to multipath measurements for a single target. We consider the problem of multipath measurements clustering for OTHR, where multipath measurements recognition and measurements clustering are solved at the same time. In the OTHR measurement model it is assumed that a target can generate at most one measurement through an ionospheric propagation path, and therefore multipath clustering constraints need to be considered.

In this paper, by extending affinity propagation (AP) clustering to multipath constraint model, a new multipath constraint affinity propagation clustering algorithm is proposed. Each cluster is modelled by an automatically determined number of exemplars, and each measurement is assigned to the most appropriate exemplar. The multipath clustering constraint is coded to the model through two aspects. First, the measurements obtained from the same measurement and the same propagation path cannot be exemplar of each other. Second, the measurement generated by the same propagation path cannot choose the same exemplar. Then the clustering problem is transformed into an inference problem by constructing the probabilistic graphical model of multipath measurements clustering, and the max-sum belief propagation is used to approximate the maximum a posteriori probability of the clustering variables.

The main advantages of the proposed algorithm include: 1) Comparing with AP, it can model the data with more complex structure; 2) It automatically identifies the number of clusters, and its computational complexity scales quadratically in the number of measurements and the number of propagation paths.

To set up the simulation, we use common OTHR simulation scenarios, which have four ionospheric propagation paths and 8 targets. Performance metrics include detection rate, root mean square error and running time. The proposed algorithm is compared with the pruning version of the multiple hypothesis multipath clustering algorithm with respect to different number of targets with 4,000 Monte Carlo runs. Simulation results show that, the proposed method outperforms the multiple hypothesis multipath clustering algorithm.

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Keywords: *Over-the-horizon radar, multipath, measurements clustering, affinity propagation, belief propagation*

Staff rostering at a blood donor centre

M.W.A. Erandi [a], **M. Fackrell** [a] **and L. Zhang** [a]

[a] *School of Mathematics and Statistics, The University of Melbourne, 813 Swanston Street, Parkville VIC 3010*

Email: aerandi@student.unimelb.edu.au

Abstract: The Australian Red Cross Lifeblood collects blood from almost entirely non-remunerated voluntary donors. A satisfying service must be offered to guarantee that donors successfully finish the donation process and return to donate blood frequently. Donor satisfaction is closely linked to the amount of time spent in the donor centre. Long assessment and waiting times adversely affect the donor experience, and consequently, the donor return rate. These waiting times can be reduced by making the donor flow more efficient via optimal staff rostering. Our objective is to implement a method for determining the optimal staff roster for a typical day based on the predicted staffing demand via two phases. To begin, we establish the minimum staffing requirements to ensure that the system's predicted average waiting time does not exceed a specified thresh-old. In the second phase, we find an optimal staff roster that meets the minimum staffing requirements. We conduct the preliminary analysis based on data acquired from the Melbourne CBD blood donor centre, which has a donor arrival system featured by a mix of appointment-based arrivals, random arrivals, and no-shows. Since calculating waiting times is non-analytic in such a complex system, we develop a simulation model that captures almost all the uncertainty in the donation process and use it to compute the average waiting time with respect to a staff configuration. We propose a simulation-based simulated annealing algorithm that seeks the minimum number of employees to meet varying demand requirements over a single day, divided into half-hour short periods. To efficiently evaluate the objective function, we develop a neighbourhood searching method for generating new solutions based on the staff occupancy levels. A sensitivity analysis is performed to determine the essential parameters in phase 1. When constructing the staff roster, the minimal staffing requirement calcu-lated in phase 1 serves as a lower bound. The second phase entails determining flexible start times and varying shift durations. Furthermore, assigning meal and rest breaks for each shift based on labor standards is critical and complicates the staff rostering challenge. Therefore, we find an optimisation procedure for deriving the minimum staff roster for a single day.

Keywords: *Staff rostering, blood donor centre, stochastic optimisation, simulation*

On optimal stopping problems with positive discounting rates and related Laplace transforms of first hitting times in models with geometric Brownian motions

P. V. Gapeev [a]

[a]*London School of Economics, Department of Mathematics, Houghton Street, London WC2A 2AE, United Kingdom*
Email: p.v.gapeev@lse.ac.uk

Abstract: We derive closed-form solutions to some optimal stopping problems for one-dimensional geometric Brownian motions with positive discounting rates. It is assumed that the original processes can be trapped or reflected or sticky at some fixed lower levels and the conditions on the gain functions imply that the the optimal stopping times turn out to be the first times at which the processes hit some upper level which are to be determined. The proof is based on the reduction of the original optimal stopping problems to the to the equivalent free-boundary problems and the solutions of the latter problems by means of the instantaneous-stopping and smooth-fit conditions for the value functions at the optimal stopping boundaries.

We also obtain explicit expressions for the Laplace transforms or moment generating functions (with positive exponents or parameters) of the first hitting times for the geometric Brownian motion of given upper levels under various conditions on the parameters of the model. In particular, we determine the upper bounds for the hitting levels and given positive exponents or parameters of the Laplace transforms for which the resulting expectations are finite under various relations between the parameters of the model. Moreover, we determine the upper bounds for the positive exponents or parameters of the Laplace transforms and given hitting levels for which the resulting expectations are finite under various relations between the parameters of the model.

The main aim of this short article is to derive closed-form solutions to the optimal stopping problem of (2) for the geometric Brownian motion X defined in (1) with a positive exponential discounting rate $\lambda > 0$. We assume that the process X can be trapped or reflected or sticky at some level $a > 0$ and the gain function $G(x)$ is a twice continuously differentiable positive and strictly increasing concave function on $(0, \infty)$. Optimal stopping problems for one-dimensional diffusion processes with *negative* exponential discounting rates have been studied after Dynkin (1963) by many authors in the literature including Fakeev (1970), Mucci (1978), Salminen (1985), Øksendal and Reikvam (1998), Alvarez (2001), Dayanik and Karatzas (2003), and Lamberton and Zervos (2013) among others (we refer to Øksendal (1998, Chapter X), Peskir and Shiryaev (2006) and Gapeev and Lerche (2011) for further references). The consideration of optimal stopping problems for diffusions with *positive* discounting rates was initiated by Shepp and Shiryaev (1996) and then has been continued by other authors in the literature (we refer to Gapeev (2019) and Gapeev (2020) for further references). In this short article, we also present explicit expressions for the Laplace transforms (with positive exponents or parameters) of the first hitting times of given upper levels under various conditions on the parameters of the model (see Borodin and Salminen (2002, Part II) for other computations of the Laplace transforms of first hitting times).

Keywords: *Optimal stopping problem, positive discounting rate, Brownian motion, first hitting time, Laplace transform or moment generating function.*

Simulating population-size-dependent birth-and-death processes using CUDA and piecewise approximations

S. Hautphenne [a] and **B. Patch** [a]

[a] *School of Mathematics and Statistics, The University of Melbourne, Parkville, Victoria, 3010, Australia*

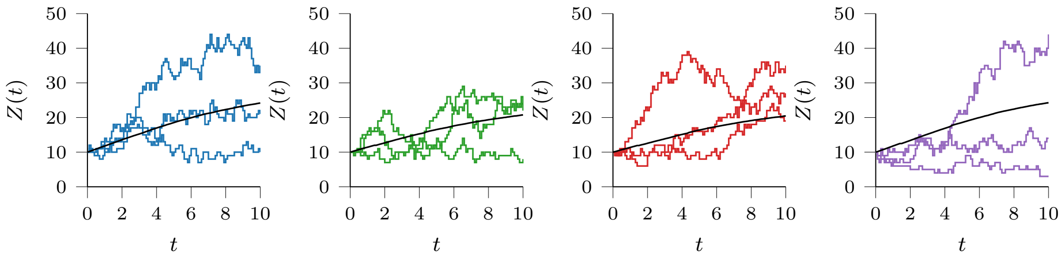
Email: patch@unimelb.edu.au

Abstract: Birth-and-death processes (BDPs) are widely used to model stochastically evolving populations in ecology, genetics, and epidemiology, among others. Population-size-dependent BDPs (PSDBDPs) allow the rate at which individuals give birth and die at any moment in time to depend on the total number of individuals present in the population at that time.

Explicit expressions for the probability distribution and expected value of the future population size at a particular time, conditional on the current population size, are not available in general for PSDBDPs. Simulation is a viable avenue for estimating the probability distribution and expected value of interest. Due to the large number of samples that may need to be simulated in order for accurate estimates to be obtained, simulation may, at first sight, appear to be prohibitively computationally expensive. In this paper we compare the classic exact simulation algorithm with more recent piecewise (or "tau-leaping") approximations that are designed to speed up the simulation process. We also introduce a novel piecewise approximation to PSDBDPs based on linear BDPs. Sample paths generated using each algorithm are displayed in Figure 1, which is discussed in more detail in the paper.

We show that for CPU-only implementations, our new algorithm compares favourably against both exact simulation and other, less accurate, piecewise approximations. In addition to this we investigate a graphics processing unit (GPU) implementation of the exact algorithm. This GPU implementation is able to use CUDA to output estimates of these quantities at a tiny fraction of the time taken by CPU-only implementations.

Our experiments indicate that the CUDA version of exact simulation is the fastest of the approaches we tried. When only a CPU is available, in our experiments our new piecewise approximation is as accurate as exact simulation, but noticeably faster. In particular, the computational burden of our approximation is unchanged by an increase in population size; while on the other hand exact simulation consistently becomes more time consuming as the population increases. Our piecewise approximation is of comparable speed to, but far more accurate than, the classic piecewise approximations we compared it with. It is also robust to increases in the length of the subintervals making up the piecewise approximation — it only suffers from a minor decrease in accuracy as the subintervals are taken to be larger.



(a) Alg. 1 (CPU) (b) Alg. 2 (c) Alg. 3 (d) Alg. 4

Figure 1. Sample paths $z_{10,l}(t)$ (coloured) and the average of 10^4 sample paths $\hat{m}_{10}^{10^4}(t)$ (black) of an SIS model (Verhulst model with $\alpha = 1/N$ and $\beta = 0$) with $\gamma = 0.75$, $\nu = 0.5$, and $N = 100$, generated using different algorithms.

Keywords: *Birth-and-death processes, tau-leaping, simulation, piecewise approximation, CUDA*

Prior versus data: A new Bayesian method for fishery stock assessments

Y. Lei [a], **S. Zhou** [b] **and N. Ye** [a]

[a]*School of Mathematics and Physics, The University of Queensland, St Lucia, QLD 4072, Australia*
[b]*CSIRO Oceans and Atmosphere, 306 Carmody Road, Saint Lucia, Brisbane, QLD 4072, Australia*
Email: yeming.lei@uq.edu.au

Abstract: Bayesian method has become an indispensable technique in fisheries stock assessments, due to its flexibility and effectiveness in handling the various types of uncertainties in stock assessments, such as a lack of knowledge about the biological process and the presence of process and measurement errors. In particular, in the data-limited or data-moderate case, while frequentist methods may struggle to provide satisfactory results, the Bayesian approach can obtain more accurate estimates with its ability to incorporate the existing knowledge in the form of prior distributions on the models.

The effectiveness of Bayesian methods stems from its ability to combine the prior and observation in a prin-cipled way using the Bayes theorem. However, specifying a good prior can be a difficult task, and a poor prior may lead to a poor parameter estimate, even though the data are of high-quality for a frequentist-based approach, such as maximum likelihood estimation, to obtain accurate parameter estimates.

We developed a novel Bayesian method called *multi-pass Bayesian estimation* (MBE) that allows us to adjust the relative importance of the prior and the data, and thus offers more flexibility in combining the prior and the data. The MBE enables such flexibility to control the relative importance of the prior and the data by performing multiple Bayesian updates using the given dataset. By controlling the relative importance of the prior and the data, we obtain a spectrum of different interpolations of them, including only relying on the prior which completely ignores the data, the standard Bayesian posterior which combines the prior and the data using the Bayes rule once, and distributions that essentially rely just on the data.

We applied the MBE to a Bayesian surplus production model based on the popular Schaefer population dy-namics model. Results in simulation studies show that the MBE provides more accurate parameter estimates than the standard Bayesian approach, in various settings with different levels of uncertainties in the data. The method is applicable to any Bayesian stock assessment models, and our results suggest that further investiga-tion of the method's performance is promising.

Keywords: *Bayesian method, Multi-pass Bayesian estimation, maximum likelihood estimate, fishery stock assessments*

A Change-Point Test for Autoregressive Processes Using a Harmonic Mean P-Value

L. Ma [a], **G. Sofronov** [a]

[a]*Department of Mathematics and Statistics, Macquarie University, Sydney, Australia*
Email: georgy.sofronov@mq.edu.au

Abstract: In many different applications, it is important to know if time series data is generated from a single underlying mechanism or not. This problem, known as a change-point problem, can be formulated as a multiple hypotheses testing problem. In this paper, we propose a harmonic change-point test (HarmonicCPT) to identify and validate change-points in an autoregressive process. The method consists of two steps. First, we develop likelihood ratio based scan statistics on gathering the local information by comparing two adjacent sequences within each scanning window. The corresponding p-values are collected from each test. Any changes in mean, autoregressive coefficients, or variance lead to rejections of the null hypothesis that the data is generated from the same process within the scanning window. Next, we calculate a harmonic mean p-value by combining all of the tests on which the decision that whether to reject the global null hypothesis depends. The simulation study shows that the proposed scan statistic is quite sensitive to the variance change, and the harmonic mean p-value procedure is efficient in detecting the significant p-values.

Keywords: *Change-point test, autoregressive process, multiple testing, harmonic mean p-value*

Use of auxiliary information in estimation of the finite population mean: An exponential type of estimator

[a]Kalim Ullah, [b] Hudson, I. L., [c] Cheema, S. A. [a] Khan, A. [a]Abdu-R-Rahman and [d] Hussian, Z.

[a] *Department of Statistics, Quaid-i-Azam University Islamabad, Pakistan* [b] *Mathematical Sciences, College of STEM, School of Science, Royal Melbourne Institute of Technology (RMIT), Melbourne, Australia.*

[c] *Department of Applied Sciences, National Textile University Faisalabad, Pakistan.*

[d] *Department of Social and Allied Sciences, Cholistan University of Veterinary and Animal Sciences, Bahawalpur, Pakistan.*

Email: *irene.hudson@rmit.edu.au*

Abstract: The use of auxiliary information has a long history in statistical theory and estimation procedures. The utility of supplementary knowledge becomes vital when information about the study variable is limited. In this paper, we present a more competent mechanism to utilise auxiliary information in the estimation of the finite population mean. We propose a new exponential type of estimator for the estimation of finite population mean in the scenario where a simple random sampling scheme is adopted. Our proposed procedure is based on the dual use of the supportive information to maximise additional gain and involves the use of the mean of the auxiliary variable along with its rank to increase the extent of relevant information. The comparative performance of the proposed scheme is demonstrated with respect to 10 most used, classic, and some recent procedures in estimation theory literature. These are the classic mean estimator $\hat{\bar{Y}}_{srs}$, the so-called traditional ratio, product, and regression estimators $\hat{\bar{Y}}_R$, $\hat{\bar{Y}}_P$ and $\hat{\bar{Y}}_{reg}$, respectively, along with the difference type estimator $\hat{\bar{Y}}_{R.D}$. In addition, the more recent estimators investigated are the ratio-product exponential type $\hat{\bar{Y}}_{S,RP}$, difference exponential type $\hat{\bar{Y}}_{GK}$, ratio exponential $\hat{\bar{Y}}_{BT,R}$, product exponential $\hat{\bar{Y}}_{BT,P}$ and the ratio-product-exponential $\hat{\bar{Y}}_{SHG}$, all used for comparison. Moreover, we consider three data sets of a multi-disciplinary nature, encompassing health surveillance, industrial production and poultry. The choice of data sets is mainly motivated by two reasons; (i) these data sets have been topics of contemporary techniques and, (ii) the considered data sets do offer a wide range of parametric settings, including lower extent of correlation between the study variable with the auxiliary variable and they also vary in sample sizes.

In addition, we consider cases of a higher positive and higher negative degree of linear relationship extant between the study variable and auxiliary variable in these data sets. Along with the opportunity of conducting a fair comparison of our suggested strategy with contemporary techniques, the above approach allows for us to observe various patterns prevalent in the resultant gains of our newly devised scheme. Improvements are quantified by the mean square errors of the competing estimators, which are further transformed into relative percentage efficiencies to attain a comprehensive view of the research effort. Overall, we observe a noticeable amount of decrease in mean square error for our proposed estimator as compared to existing estimators, evident for all the considered data sets. However, there are a few observant patterns in the efficiency gains coinciding with assigned pre-defined parametric settings, in that the extent of the correlation between the auxiliary variable and output variable plays a pivotal role in the performance of estimation procedures. The improvement in the efficiency becomes more obvious as the degree of linear relationship between the output variable with the auxiliary variable strengthens. For example, minimum gain in percentage relative efficiencies (PREs) is observed for the 1st data set, wherein the correlation coefficient, $\rho_{out,aux}$, remains minimal. For the two other data sets the gain remains clearer as the correlation coefficient takes higher values, say, $|\rho_{out,aux}| > 0.85$. We also note the varying performance hierarchy among contemporary estimators with respect to varying features of each population. Our proposed estimator outperforms the existing methods studied here in all cases. The mathematical expressions for the bias and mean squared error of the proposed estimator is derived under the first order of approximation. The theoretical and empirical studies show that the proposed estimator performs uniformly better than the existing estimators in terms of the percentage relative efficiency. We advocate that in future exponential smoothing will be used to quantify changes given updates by auxiliary information and recent observations.

Keywords: *Auxiliary information, exponential type estimator, mean estimation, ranks, simple random sampling*

Estimating tail probabilities of random sums of scale mixture of phase-type random variables

H. Yao [a] **and T. Taimre** [a]

[a] *School of Mathematics and Physics, The University of Queensland, Brisbane QLD 4072, AUSTRALIA*

Email: hui.yao@uq.net.au

Abstract: We consider the problem of estimating tail probabilities of random sums of scale mixture of phase-type distributions — a class of distributions corresponding to random variables which can be represented as a product of a non-negative but otherwise arbitrary random variable with a classical phase-type random variable. Our motivation arises from applications in risk, queueing problems for estimating ruin probabilities, and waiting time distributions respectively. Classical rare-event simulation algorithms cannot be implemented in this setting because these methods typically rely on the availability of the cumulative distribution function or the moment generating function, but these are difficult to compute or not even available for the class of scale mixture of phase-type distributions. In this paper, we address these issues and propose alternative simulation methods for estimating tail probabilities of random sums of scale mixture of phase-type distributions; our algorithm combines importance sampling and conditional Monte Carlo methods. The empirical performance of the method suggested is explored via numerical experimentation.

Keywords: *Asmussen–Kroese Estimator, Conditional Monte Carlo, importance sampling, scale mixture of phase-type distribution*

LASSO-type regularization with nonparametric Bernstein copula estimation

A. Zhang [a], **A. Prokhorov** [a] **and P. Radchenko** [a]

[a] *Business School, The University of Sydney, Sydney, 2006, Australia*
Email: aixi.zhang@sydney.edu.au

Abstract: For Modelling the dependence structure is an important aspect of data mining and statistical learning in financial risk management and related fields. Copula is well-recognized as a flexible approach to model the dependence. It enables the estimation of the copula density function and different marginal density functions to be done separately. According to the invariance property of copula, the full dependence between random variables can be captured by the copula with any shape of the marginal distribution. An accurate and efficient method in copula density estimation is vital in modelling dependence.

Constraints of shape and misspecification of parametric copulas for complex financial data necessitate a flexible model. We propose a penalized nonparametric Bernstein copula approach. The Bernstein copula (Sancetta & Satchell 2004) has the property to estimate any two-dimensional copula uniformly on $[0,1]^2$. It employs beta copula density functions as smoother and by adjusting the weight, it can adapt to different conditions. The nonparametric approach of Bernstein copula estimation provides great flexibility to capture different dependence structures, especially to a given dataset.

Since the nonparametric models involve unknown parameters in infinite-dimensional parameter spaces, it is computationally complicated to be estimated by finite samples. Moreover, optimizing a sample criterion over an infinite-dimensional space may lead to undesirable large sample properties, like inconsistency and/or slow rate of convergence (Chen 2007). The method of sieve is employed to remedy this issue. Instead of directly optimizing the criterion function over an infinite-dimensional space, the method of sieve provides a sequence of approximating space, which is comparably less complex but dense in the original infinite-dimensional space. We utilize the Bernstein polynomials as a sieve. It ensures the outcome sieving is a suitable copula density (non-negative, integrated to one and marginal distribution is uniform). Its uniform convergence rate is comparably faster than the other tensor product sieves (Panchenko & Prokhorov 2016).

In addition, an adaptive LASSO (Zou 2006) penalty is used to reduce the risk of overfitting and efficiency loss. The weights of the penalty are set as reciprocals of the empirical copula in order to impose sparsity. The finite sample behaviors of the proposed model are investigated and the comparison with its counterparts is done through Monte Carlo simulations. We also demonstrate merits of our proposed model both theoretically and empirically.

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Keywords: *Dependence structure, Nonparametric Bernstein copula, sieve, regularization*

EXTENDED ABSTRACT ONLY

Impact of a dispersed gas phase on radiative transfer

Felix Egger[a b], **Damien J. Batstone**[b] and **Christopher DeGroot**[c]

[a]*School of Chemical Engineering, University of Queensland, St Lucia 4072, Australia*
[b]*Australian Centre for Water and Environmental Biotechnology (ACWEB, formerly AWMC), University of Queensland, St Lucia 4072, Australia*
[c]*University of Western Ontario, London, Ontario, Canada*
Email: f.egger@uq.edu.au

Abstract: Radiative fields in bubbly (gas-liquid) systems are common in environmental systems (*e.g.* gas bubbles produced by algae in ocean water), and also in engineered systems (*e.g.* UV-disinfection in wastewater treatment, photo-catalytic- and photo-bio-processes). Typically, the dispersed gas phase changes the radiative fields, which directly couples back to the liquid phase and photo-dependent process in the liquid (*i.e.* distribution of radiative energy for algae; disruption of disinfection by bubbles, potentially resulting in unsafe discharge). The influence of a dynamic bubble size distribution on radiative transfer has not been incorporated into common modelling approaches, even though bubble size distributions are often important in biological processes, where substrates are delivered via the gas phase. Depending on the bubble size, incident radiation may be reflected, refracted and attenuated on bubble surfaces, which macroscopically, can be approximated as scattering. Computational fluid dynamics (CFD) was used to analyse the impact of variable bubble sizes on mass and radiative transfer. The aim was to approximate refraction and reflection phenomena on single bubble surfaces, with a field function for multi-phase CFD simulations. Radiative transfer was solved for single bubbles with a diameter ranging from 0.1 to 100 mm, irradiated with a collimated beam. The calculations were performed using OpenFOAM-6®and custom radiation libraries. The resulting reflection and refraction on the bubble surface diverted the radiation from the collimated beam into other directions. Reflection and refraction patterns were approximated with a Henyey-Greenstein scattering phase function, and the model asymmetry factor g was determined as a function of the bubble size. The factor g describes the direction of scattering, from forwards (g=1), over isotropic (g=0.5), to backwards (g=-1). The asymmetry factor field function was approximated with an exponential decay model of the form $g(d_b)$=a×exp(-bd_b)+c. Limits were g=0.88±0.05 for bubble size d_b=0.1mm, approaching pure forward scattering, and g=0.54±0.02 for bubble size d_b=100mm, closer to isotropic scattering. Secondly, a dynamic multi-phase and radiation coupled model was implemented in OpenFOAM-6®to study the impact of different bubble sizes and gas void fractions on the redistribution of radiative energy and gas-liquid mass transfer. Two cases with bubble size 0.1 mm and 1 mm showed that gas-liquid mass transfer increased substantially with smaller bubble sizes. The radiative transfer at low gas volume fractions ($\alpha_g \approx 10^{-5}$) and bubble size 0.1 and 25 mm resulted in a significant redistribution of radiative energy with larger bubble sizes. Scattering was observed at a higher gas volume fraction (α_g=0.5), and bubble sizes 0.1 and 25 mm with a minor difference between the bubble sizes. Local differences were observed depending on gas volume fraction and bubble size. Specifically, increases in the radiative intensity close to the emitter were observed. The redistribution of radiative energy causes deviation from the standard radiative adsorption function (Lambert-Beer) such that fluid packets close to the emitter receive more radiation, while those away from the emitter receive less. The reduced intensity may be problematic for engineered systems requiring a set level of radiation intensity (*e.g.* sanitation purposes), particularly where bubbly flows are non-uniform in time or space.

Keywords: *Gas-liquid-radiative systems, radiative energy transport, computational fluid dynamics, multi-physics systems*

CFD solver validations for simulating passively pitching tandem wings in hovering flight

Q. Huang [a], S. Mazharmanesh [a], F.-B. Tian [a], J. Young [a], J. C. S. Lai [a], and S. Ravi [a]

[a] *University of New South Wales at Canberra, GPO BOX 7916, Canberra ACT 2610, Australia*
Email: qxhuang2013@gmail.com

Abstract: Wing pitching motion in insect flapping flight has been recognized as a passive phenomenon induced by inertial and aerodynamic forces. Inspired by the insect flight, passively pitching flapping wings have been implemented in micro aerial vehicles (MAVs) designs. The pitching angle of the flapping wings is passively modulated by an elastic hinge using a torsional spring. In order to understand the complex passive pitching mechanisms, various experimental and numerical efforts have been made. However, the passive pitching mechanisms in tandem ipsilateral wings (e.g. dragonfly) remain unclear as the wing-wing interactions are complex. Here, passive pitching of tandem rectangular wings in free hovering condition is numerically simulated using an immersed boundary-lattice Boltzmann method (IB-LBM). Validation of the solver was performed by simulating rectangular flapping plate within prescribed kinematics and a rigid fruit fly wing with passive pitching. Good agreement of results between current computations and published data were observed, suggesting that the present computational fluid dynamics (CFD) solver can accurately compute passively pitching flapping wing systems. The high-fidelity and efficiency were also investigated by performing grid convergence studies and comparing the computational time with previously published data. This study provides additional data for benchmarking of CFD solvers in the simulation of passive flapping wings. The benchmark is also extended by simulating passive pitching of tandem dragonfly wings in hovering flight.

Keywords: *Passive pitching, fluid-structure interaction, tandem flapping wings, insect flight, dragonfly*

Convective flows in vegetated water bodies

Muhammadhn M. Khalid[a], Edoardo Daly[a] and Murray Rudman[b]

[a] *Department of Civil Engineering, Monash University, VIC 3800, Australia*
[b] *Department of Mechanical and Aerospace Engineering, Monash University, VIC 3800, Australia*
Email: muhammadh.khalid@monash.edu

Abstract: The littoral zone of water bodies, such as lakes and wetlands, is often vegetated. Vegetation shading and littoral slope cause differential heating that drives natural convection in the water body. This convective water exchange can transport pollutants and nutrients between the littoral and the limnetic (i.e., the part of the water body open to receive light) regions, as well as flush the littoral zone. Studies that consider the combined effects of different vegetation covers and slopes are limited to a small range of natural conditions. This study investigates natural convection in the littoral zone due to littoral slope and vegetation shading in natural water bodies for a wide range of natural conditions.

The convective flow is modelled coupling the Navier-Stokes equations to the heat transfer equation; the Boussinesq approximation is employed, thus assuming that changes in fluid density only affect the body force in the momentum equation. The vegetation is approximated as a representative porous medium, which generates resistance to the flow. Smoothed Particles Hydrodynamics (SPH) is used to solve the system of equations describing the convective flow in the vegetated littoral zone. The change in the flushing time, flow rate and flow velocity are calculated and their impacts are analysed for a range of natural conditions applicable to natural water bodies.

Some scenarios are presented associated with flows during the day and night. During the day, the vegetation provides shade to the water with a lower heat flux at the water surface in the littoral zone; conversely, at night, the vegetation traps heat with the water surface in the limnetic zone being cooler than the littoral zone. The flow mechanisms and the resulting flow patterns are different between day and night, with the littoral water flowing out as an undercurrent during the day and as a surface current during the night. It takes longer to flush the littoral water during the night compared to the day, and the mixing of littoral and limnetic water is minimal during the day. Convective flow condition in a shallow water body can be estimated from the quantitative results of this study. Further, these results can be used to construct wetlands with a specific flushing time, flow rate, and flow velocity, which are vital for controlling resuspension or transport of pollutants.

Keywords: *Natural convections, SPH, vegetated water bodies*

An immersed boundary-regularised lattice Boltzmann method for acoustic simulations of FSI problems

Methma Rajamuni[a], **Zhengliang Liu**[b], **and Fangbao Tian**[a]

[a] *School of Engineering and Information Technology, University of New South Wales Canberra 2612, Australia*
[b] *Department of Ocean Science and Engineering, Southern University of Science and Technology, Shenzhen 518055, China*
Email: m.rajamuni@adfa.edu.au

Abstract: With the development of computational technologies, examining aeroacoustics in fluid-structure interaction (FSI) problems is becoming more popular. In this initial work, we developed an efficient numerical methodology to study aeroacoustics in FSI problems, for example, the noise of flapping insect wings.

The length scale of sound waves is significantly smaller than that of aerodynamic fluctuations of macro variables. Consequently, a heavy spatial domain with high resolution is required together with an extremely small time step to capture these soft acoustic signals in computational aeroacoustic simulations. It is challenging to simulate acoustics problems using the conventional methods of solving Navier-Stocks (NS) equations, as higher-order accuracy, low-dispersion and low-dissipation spatial discretisation and time marching schemes are necessary. Nevertheless, the lattice Boltzmann method (LBM), which describes the evolution of mesoscale velocity distribution functions, based on the free-streaming and collision is intrinsically suitable for aeroacoustic simulations. The simple nature of the LBM, efficiency with parallel simulations, small-time steps than in the NS method, and large spatial resolutions, make LBM more attractive for acoustic simulations.

LBM has been used intensively for different types of fluid problems. Immersed boundary method (IBM) is a well-established technique that can handle various types of boundary conditions. In particular, it is widely used to model the fluid-structure interface of FSI problems. Thus, an immersed boundary-lattice Boltzmann method (IB-LBM) was developed for this study. There are many different versions of LBMs with distinct collision operators. The Bhatnagar-Gross-Krook (BGK) collision operator is the simplest and most common one. In general, the BGK operator is second order in accuracy, and there is a high probability to encounter stability issues, especially in acoustic simulations. Therefore, the recursive and regularised (RR) BGK collision operator, which considers higher-order Hermit polynomials, was used in this study. The multi-block grid refinement was used to reduce the computational cost of a simulation. At the outer boundary of the domain, a non-reflective boundary condition was employed to overcome the reflections of sound waves.

The von Neumann analysis was conducted investigating the stability of the regularised LBM. It was found that the accuracy and stability of the regularised LBM were improved when the collision operator was computed from the Hermite polynomials up to 4th order instead of the 2nd order. In addition, two benchmark cases: the propagation of an acoustic monopole and point source and the sound generated by a stationary cylinder in a uniform flow were conducted, as validation studies. Predictions given by the IB-regularised LBM showed a good agreement with numerical simulations and analytical solutions reported in previous publications, demonstrating the capability of the IB-regularised LBM presented in this study for acoustic problems.

Keywords: *IB-LBM, regularised BGK operator, acoustic problems, multi-block grid refinements, perfectly-match layer, stability analysis*

Measuring the sensitivity of model inputs in childhood obesity modelling

Simon K Chiu [a,b,c], **Louise Freebairn** [b,c,d], **Jo-An Occhipinti** [b,c,d], **Louise Baur**[b,e] **and L. Kurt Kreuger**[f]

[a] *School of Public Heath, University of Sydney*
[b] *The Australian Prevention Partnership Centre*
[c] *Brain and Mind Centre, Faculty of Medicine and Health, University of Sydney*
[d] *Computer Simulation & Advanced Research Technologies (CSART), Sydney, Australia*
[e] *The University of Sydney, Children's Hospital Westmead Clinical School, Westmead, Australia*
f Kreuger Consulting LLC
Email: schi9002@uni.sydney.edu.au

Abstract: The use of system dynamic models to explore the complex dynamics of childhood overweight and obesity has grown significantly over the last decade (Xue et al, 2018). However, modelling health problems that are influenced by human behaviours leaves many model inputs with wide intervals of uncertainty, often with many sources of bias which are measured infrequently. Further more, population models of obesity are non-linear and have variable interactions leading to a highly complex parameter space to explore and validate. A robust sensitivity analysis is needed to explore the model structure and ensure that the model adequately reflects the system.

Decision Support Tool for Preventing Childhood Overweight and Obesity in Australia (DiSCAO) was developed as a system dynamic model. The model was developed in conjunction with a series of participatory workshops. The workshops enabled the modelling team to understand the complex nature of child and adolescent obesity by leveraging expert knowledge of existing literature and data sources. The open population model is stratified by gender, age and BMI categories, where the dynamics transitions between BMI categories are determined by inputs into an energy balance equation. However, measures of dietary intake and energy expenditure are difficult to quantify as they have a range of potential biases including social stigma, recall bias and measurement error, resulting in potential miss representation of health behaviour in the model. A series of sensitivity analysis is needed to ensure that the model structure aligns with relationships known to occur in the system.

The aim of a sensitivity analysis is to measures how changes in model inputs affect model outputs (Saltelli, 2008). This is an important step in validating the model as it helps to corroborate the model outputs, identify critical input values, and also prioritise future research (Saltelli, 2008). Commonly in system dynamics modelling validation is conducted using a combination of theoretical and empirical tests, including formal model reviews, structure and parameter confirmation, boundary adequacy tests, extreme conditions test and exploration of modelled behaviour patterns (Barlas, 1996). Empirical model testing such as parameters confirmation and extreme value testing can be computationally taxing. As a result, often only a small subset of the model input parameters are explored.

The sensitivity analysis of the DiSCAO expends extreme value testing by using measures of sensitivity such as correlations and regression coefficients as well as variance- and derivative-based measures to explore the model structure. In this presentation we will discuss finding from a local and global sensitivity analysis, examine the usefulness of a range sensitivity measures and give insights into the challenges and limitations of conducting sensitivity analysis in large complex model of non-communicable diseases.

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Keywords: *System dynamic modelling, sensitivity analysis, childhood obesity*

A simplified approach to model performance assessment accounting for uncertainty

Barry Croke

Mathematical Sciences Institute and Fenner School of Environment and Society, Australian National University, Canberra, ACT, Australia
Email: barry.croke@anu.edu.au

Abstract: Objective functions have built-in assumptions regarding the uncertainties in model residuals. Objective functions that are based on the sum of squared residuals (e.g. NSE, RMSE) assume that the uncertainties are independent and identically distributed. Being independent means that the error in the model output at one time step is not related to the error in any other time step. Identically distributed means that the uncertainty is the same at all time steps. Unfortunately, it is rare for both these conditions to be met, so evaluating models using such objective functions is fundamentally flawed.

The Box-Cox transformation (Box and Cox, 1964) is a simple way of modifying objective functions to account for different distributions of uncertainties, enabling the requirement of identically distributed uncertainties to be modified. Generally, the one-parameter Box-Cox transformation is used, with the residuals used to estimate the value of the parameter. While such an approach is easy to implement, it is limited in two ways. Firstly, the Box-Cox transformation has a second parameter that allows the use of the non-positive values of the first parameter in cases where the observed or modelled values are zero. This gives greater flexibility to the Box-Cox transformation at the cost of having to estimate a second parameter. Secondly, the use of residuals to estimate the parameters of the Box-Cox transformation is problematic and should be avoided. Instead, the uncertainty in the residuals should be used to estimate the parameters. This raises the problem of estimation of the uncertainties. However, only a reasonable guesstimate of the parameter values is needed to improve the result. This should be based on a combination of sensitivity analysis of the model and understanding of the uncertainty in the data used by the model.

Addressing the condition of independence requires a change to the formulation of objective functions. Models have memory due to the use of internal states. This induces serial correlation in the error in the modelled output (note this is not the model residual; rather it is the propagation of error in the model inputs through the model). Observed values can also be dependent on each other. For example, with streamflow data, uncertainty in the rating curve will induce serial correlation in the observed streamflow data. This is in terms of the water level, but also produces temporal serial correlation. Ignoring the dependence in observed and modelled values means that the objective function is not making use of all the information available in the time series, thereby increasing uncertainty in the calibrated values. See Croke (2009) for an example of modifying an objective function to account for dependence.

This presentation will discuss the implications of using the Box-Cox transformation to improve evaluation of model performance and a simple generalised application approach.

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Keywords: *Model performance, calibration, uncertainty*

The Padé-Laplace formalism for carbon and climate responses

I. G. Enting [a]

[a] *CSIRO Climate Science Centre, Oceans and Atmosphere, Aspendale, VIC, Australia*
Email: ian.g.enting@gmail.com

Abstract: Impulse response functions have been used extensively in studies of CO_2 (carbon dioxide), the carbon cycle and its interactions with the climate system. The response functions have been presented as compact descriptions of model behaviour as well as being used computationally, including as representations of subsystems in models.

Response functions for emissions of greenhouse gases have also been important because of being used to define the Global Warming Potential which is used to compare the importance of different greenhouse gases.

The Laplace transform formalism is convenient for analysing aspects of response functions because convolutions transform into products of transforms. The Laplace transform has been used in various ways to illustrate connections within the carbon-climate system, but generally has not been used for quantitative calculations.

This paper explores the use of Laplace transforms as a computational tool for investigating CO_2 and climate. The Padé-Laplace approach consist of taking a Maclaurin series or Taylor series expansion of the Laplace transform of a response function and fitting the leading terms to a ratio of polynomials. Such approximations are known as Padé approximants.

Approximants of appropriate order can be expressed as sums of partial fractions. Therefore such approximations can be used to give low-order expressions as sums of exponentials in the time domain.

Results presented here illustrate a number of important cases:
(i) the impulse response for CO_2 is transformed to give an expression for what is called the concentration feedback – the extent to which increases in atmospheric CO_2 cause uptake of carbon into land and ocean systems. The low-order approximants give a better representation than the common practice of expressing this feedback as a constant known as the beta-factor.
(ii) The feedback around the loop of the coupled carbon-climate system is expressed as a gain operator whose response is derived by combining model estimates of CO_2 response with and without feedback. Low-order approximants provide a way of estimating the gain, when combining ice-core CO_2 data with paleo-temperature data to estimate the climate-to-carbon influence – a quantity that is commonly approximated as a constant termed gamma.

Most calculations presented here use Padé approximants to Maclaurin series of response functions in the transform domain. Consequently, they most accurately capture the long-term behaviour in the time domain relevant for stabilising climate forcing. Applying the Padé-Laplace method using Taylor series expansions gives the potential for investigations of decadal to century scale global change. Such studies are in progress.

Keywords: *Carbon dioxide, climate, Laplace transforms*

Local Conductivity Recovery Formulas for Four-Point Probe in Electrical Resistivity Tomography Dedicated to Bob Anderssen's 82th Birthday

Agah D. Garnadi [a]

[a]*Ronin Mathematician, Cijerah II, Gg Bungur IV No 108, Melong, Cimahi, Indonesia,40534*

Email: agah.garnadi@gmail.com

Abstract: We consider the inverse electrical impedance problem in the case of piece-wise constant conductivity with the currents injected at adjacent point electrodes and the resulting voltages measured between the remaining electrodes.

In the study of a direct electrical current in a semi-infinite domain Ω, the governing equation is the following elliptic partial differential equation:

$$-\nabla(\sigma\nabla u) = q \qquad \text{in} \quad \Omega \tag{1}$$

where $\Omega \in R^d, \{d = 2, 3\}$ is a semi-infinite domain, $\sigma : \Omega \to R$ denotes the conductivity, or $\rho = 1/\sigma$ resitivity, $u : \Omega \to R$ is electrical potential, $q := I(\delta(r - s_i) - \delta(r - s_j))$ is current injection pair through point electrode at $s_{i,j}, i \neq j, 1 \leq i, j, \leq N$, where N denoting the number of electrodes. When the current source term q and the coefficient σ is given, with an appropriate prescribed boundary information for solution u so that the direct (forward) problem of u is uniquely solvable in Ω. Conversely, the recovery information about the coefficient of conductivity $\rho = 1/\sigma$, given the pair (q, g) is given, where $g(r_k) := u(r_k)$ is measured potential at point electrodes at $r_k \neq s_{i,j}$ due to current injection pattern q, is an inverse problem with σ being sensitive due to perturbation in u and q. The recovery of $\rho = 1/\sigma$ from point electrodes measurements u due to current pattern q, utilizing the equation (1), is called *Electrical Resistivity (Impedance) Tomography* with point electrode models.

Adapting the linear functional strategy from related problem in aquifer transmitivity, introduced firstly by Bob Anderssen, the conductivity/resistivity can be recovered on the zone of a domain containing the four-probe electrodes. Such local reconstruction method is needed as a preliminary step before full reconstruction of conductivity inside the domain from a set of electrode measurements, as done in electrical resistivity tomography.

Keywords: *Conductivity, resistivity, local parameter identification, piecewise constant approximations, weak formulation*

Beyond validation: assessing the legitimacy of artificial neural network models

G.B. Humphrey [a], H.R. Maier [a], W. Wu [b], N.J. Mount [c], G.C. Dandy [a] and C.W. Dawson [d]

[a] School of Civil, Environmental & Mining Engineering, University of Adelaide, Adelaide, South Australia, [b] Department of Infrastructure Engineering, The University of Melbourne, Melbourne, VIC, [c] School of Geography, University of Nottingham, Nottingham, UK, [d]Department of Computer Science, Loughborough University, Loughborough, UK
Email: wenyan.wu@unimelb.edu.au

Abstract: Artificial neural network models have been used extensively for prediction and forecasting over the last 25 years. As the data used to develop ANNs contain important information about the physical processes being modelled, it is generally implied that a model that has been calibrated (trained) and performs well on an independent set of validation data represents the underlying physical processes of the system being modelled. However, this is not necessarily the case, most likely due to problems with equifinality, where different combinations of model parameters (e.g. connection weights) result in similar predictive performance. Consequently, there is also a need to check the behaviour of calibrated ANN models as part of the validation process, which is commonly referred to as structural, conceptual or scientific validation (Figure 1). This checks whether the input-output relationship captured by the model is plausible in accordance with *a priori* system understanding.

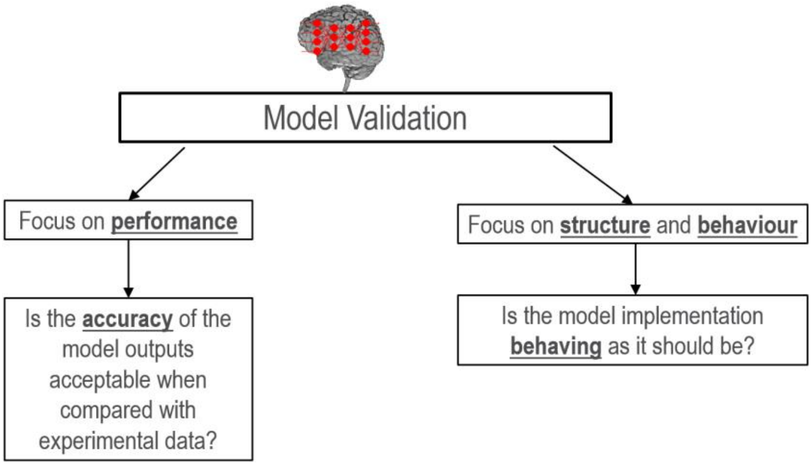

Figure 1. Importance of checking both predictive accuracy and model behaviour during ANN model validation processes

In this paper, the importance of considering structural validation is demonstrated. This is achieved by developing ANN models with different numbers of hidden nodes for two environmental modelling case studies from the literature namely, salinity forecasting in the River Murray in South Australia and the prediction of treated water turbidity at a water treatment plant based on raw water quality and the administered alum dose. The validation errors are then compared with corresponding model behaviours. This was done using the validann R-package, which caters to a range of structural validation approaches. Results show that ANN models producing the best fit to the data do not necessarily result in models that behave in accordance with underlying system understanding.

Keywords: *Artificial neural networks, multilayer perceptron, structural validation, process understanding, validann*

Comparing the physics of 1D vs. 3D atmospheric models using their linearised responses

Yi-Ling Hwong [a], **Steven C. Sherwood** [a] **and David Fuchs** [a]

[a] *Climate Change Research Centre, University of New South Wales, Sydney, 2052, Australia*
Email: y.hwong@unsw.edu.au

Abstract: One-dimensional, single-column models (SCMs) of the atmosphere are often used as a research tool to understand climate and inform model development. They contain one vertical column extracted from their parent 3D model and use the same parameterisations (physics schemes) as their parent model to represent processes that model resolutions are too coarse to resolve (e.g., individual convective cells). By virtue of their 1D setup, SCM simulations are computationally very cheap, making them an attractive tool to evaluate how parameterisations would perform in a 3D setup. There is typically a lack of feedback between model physics (parameterisations) and dynamics (large-scale flow) in an SCM, which could erode the validity of its results. However, few studies have directly compared SCM behaviour to that of its corresponding 3D model to assess the reliability of 1D results, and investigated what factors potentially influence their comparability. A related crucial task is the selection of a suitable mathematical framework to enable this comparison. This presentation addresses these questions.

We focus on the use of SCMs under radiative-convective equilibrium conditions. A multi-column model (MCM) setup is used as a proxy for a 3D model. Five convection schemes are tested. The comparability of the 1D vs. 3D behaviour is evaluated using the model's linearised responses to small tendency perturbations (linear response function, LRF). In our context, the LRF framework proposes that a model's convective responses to small perturbations of its large-scale environment is approximately linear even though convection involves myriad nonlinear processes, i.e. $d\mathbf{x}/dt = \mathsf{M}\mathbf{x}$, where $\mathbf{x}$ is the anomalous state vector of temperature (**T'**) and moisture (**q'**) around an equilibrium point. The model's linear response matrix M is hence its sensitivity Jacobian around a statistical equilibrium state between the imposed perturbation and the resulting convective processes. A study comparing the M matrices of 12 convection schemes in an SCM setup found significant disparities between them (Hwong et al., 2021), inviting the question of whether this spread also manifests itself in a more realistic 3D setup.

Our results show that the T and q sensitivities of a model in its SCM and MCM setup are very similar when convection (clouds) is disorganised and diverge strongly when convection is organised. This suggests that the comparability of 1D and 3D setup is strongly influenced by the degree of convective organisation seen in 3D: the more organised it is, the less reliable its corresponding 1D results. Nevertheless, even when convection is organised in 3D, relative differences in linear responses between the convection schemes are largely preserved between the SCM and MCM. This implies that when two schemes display similar (not necessarily identical) sensitivities in their 1D setup, they will also tend to be more similar in 3D. SCMs can thus still be useful.

Additionally, we assess the practical use of the LRF method in predicting model responses to a doubling of CO_2 in the atmosphere and demonstrate that an SCM's M matrix can accurately predict its responses to doubled-CO_2. This finding has significant implications for the use of SCMs in climate change research.

Taken together, our results have two important implications, which will be discussed in this presentation: (1) A model's linearised responses are a suitable proxy for the prediction and evaluation of its responses to various types of forcing; (2) Results of 1D models can be useful, but their validity needs to take into account the degree of convective organisation in the corresponding 3D setup.

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Keywords: *Single-column models, model evaluation, linear responses, convective parameterisation*

A robust wavelet-based bias correction approach for preserving climate change signal and correcting variability in climate model simulations

C. Kusumastuti [a, b], **Z. Jiang** [a], **R. Mehrotra** [a] **and A. Sharma** [a]

[a] *Water Research Centre, School of Civil and Environmental Engineering, The University of New South Wales, Sydney, NSW, Australia,* [b] *Department of Civil Engineering, Petra Christian University, Surabaya, Indonesia*
Email: c.kusumastuti@unsw.edu.au

Abstract: General circulations model (GCM) simulations have been extensively used to predict climate future situations. However, the systematic biases in GCM simulations prevent the direct use of the climate model for further climate studies. Bias correction approaches are then commonly used to improve the quality of raw GCM simulations. Among the first bias correction approaches, the simple linear scaling approach bias corrects the mean and standard deviation while the quantile mapping (QM) approach successfully matches the statistical distribution. The more advanced approaches, nested bias correction (NBC) approach considers the bias in the low variability of the climate simulations while multivariate recursive quantile nesting bias correction (MRNQBC) performs better than the predecessor approaches to bias correct the variability and persistence. The more recent approach namely frequency-based bias correction (FBC) offers an alternate solution for bias correcting the variability in each associated spectrum of the climate models. However, the time-varying trend of the climate models has been overlooked in most approaches mentioned here. Keeping this in mind, we propose here a robust Wavelet-based bias correction (WBC) approach for correcting biases in trends and variability of the climate models.

In the development of WBC, in order to obtain the underlying trend of climate variable time series, we perform discrete wavelet transform which forms the first important step in WBC. The mean and standard deviation correction is then applied to the underlying trend of the current climate represented by the last approximation wavelet. Next, the same statistical attributes correction is applied to the detail wavelet across frequencies to obtain the corrected variability of the current climate simulations. The correction factor obtains from the current climate correction is used for bias correcting the future climate simulations by considering our proposed delta factor (a factor derived by fitting the trend of raw current climate and observation) to ensure the continuity from current to future climate.

The robustness of WBC is demonstrated by applying it to two raw GCM simulations exhibiting opposite trends, e.g., global mean sea level (GMSL) and Arctic sea-ice extent. Results indicate that WBC corrects the bias in trend and reproduces the observed variability in the bias corrected simulations.

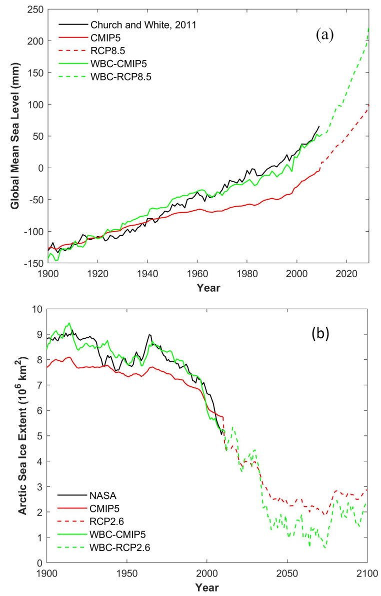

Figure 1. Wavelet-based bias correction (WBC): (a) GMSL and (b) Arctic Sea Ice Extent (Kusumastuti et al. 2021)

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Keywords: *Bias correction, climate model simulations, discrete wavelet transform, time-varying trend, variability*

Simulation and Data Analytics for a Defence Workforce Transition

K. Mortimer [a], **V. Nguyen** [a], **T. Caelli** [b] **and B. Hill** [b]

[a]*Defence Science and Technology Group, 506 Lorimer St, Fishermans Bend, VIC, 3207, Australia*
[b]*Deakin University, Waurn Ponds, Geelong, Vic 3218, Australia*
Email: katie.mortimer-murphy@dst.defence.gov.au

Abstract: The Australian Army Aviation (AAvn) is transitioning their Armed Reconnaissance Helicopter (ARH) capability from the Tiger ARH to the Apache Guardian helicopter. This transition requires retraining of all current Tiger-trained personnel in a specific time period from 2025 to 2029. While these personnel are being transitioned, the ARH capability in AAvn must be maintained. The complexity of the Defence workforce, with its hierarchical nature and highly interconnected structure, means that this transition has many workforce risks that need to be addressed through advanced planning. Further, there are many unknown variables such as workforce and resource availability, training requirements and workforce attrition. These challenges are magnified when it comes to pilots, where resource constraints and the requirement for a highly-trained workforce makes planning more difficult. Workforce analysts must have a good understanding of their workforce, and how a transition affects it, to create a robust workforce transition plan and ensure that workforce risk is minimised.

In this workforce transition analysis, a combination of simulation, Design of Experiments (DoE) and visual analysis was used to provide workforce planners with an understanding of how the AAvn pilot workforce is affected by the transition. A discrete time simulation (DTS) that models individuals, as they progress through their career and complete postings, was used to simulate the pilot workforce. The simulation engine was able to take into account personnel eligibility for particular postings and promotions.

Due to the large number of unknown variables in planning for a workforce transition, a DoE approach was used to ensure the entire problem space was effectively explored. The focus of this analysis was to determine how variations in transition courses affect the ability of AAvn to maintain its critical ARH capability, as well the entire AAvn workforce. Variations in the transition courses include transition course length, numbers transitioned per course and the delay between transition courses. This gave 42 experimental factors, so the experimental matrix was determined using a nearly orthogonal and balanced data farming design from the Naval Postgraduate School SEED (Simulation Experiments & Efficient Designs) Center for Data Farming [SEED, 2021].

Visual analytics were used to visualise the the large amounts of data produced. Complex data analytics techniques were then used to explore the AAvn workforce and find vulnerabilities, and understand why they were occurring through the analysis of relationships between inputs and outputs and between different outputs. Highly interactive visualisations of these analysis techniques were built to provide workforce analysts with the ability to further explore and understand various scenarios and outcomes.

Time series analysis was used to analyse the vulnerabilities of AAvn units throughout the workforce transition. Correlation analysis between simulation inputs and unit performance was used to determine how relationships between inputs and outputs affect these vulnerabilities. This analysis was displayed to the user via a correlation heatmap, with the user being able to explore these relationships further by clicking on the node to display the input-output relationship of that node.

A Bayesian network was fitted to the data using the PC algorithm [Spirtes et al., 1993] and parameter estimation was completed using the Expectation-Maximisation method. Effective visualisation and interactivity of the Bayesian network showed the complexity and interconnectedness of the AAvn pilots workforce, as well as allowing the user to explore in more detail specific relationships and variables. The use of Bayesian network inference allowed users to perform *what-if* analysis, without the need for further simulations, giving them a clearer understanding of the direct effect of the relationships between variables.

Keywords: *Data analytics, visual analytics, simulation, data farming*

Simulated convection responses to temperature and moisture perturbations in large eddy simulations

Timothy H. Raupach [a,b], **Yi-Ling Hwong** [a], **and Steven C. Sherwood** [a,b]

[a] *Climate Change Research Centre, University of New South Wales, Sydney, Australia,* [b] *ARC Centre of Excellence for Climate Extremes, University of New South Wales, Sydney, Australia*
Email: t.raupach@unsw.edu.au

Abstract: In numerical weather modelling, the effects of atmospheric convection are parameterised when model resolution is insufficient to simulate individual convective cells. The large variety of available parameterisations, called convective schemes, leads to uncertainty in global climate models, because different schemes react very differently to perturbations in temperature and humidity (Hwong et al., 2021). Other sub-grid effects, such as those of the planetary boundary layer (PBL), are also often parameterised. To quantify how different parameterisations affect modelled responses to perturbations, we need benchmark results that show how a weather model reacts at very high resolution so that convective and PBL parameterisations are not required. In this study we used a weather model run at large eddy simulation (LES) resolution to study perturbation responses to form such a benchmark.

The Advanced Research (AR) Weather Research and Forecasting (WRF) model was used to run idealised convection simulations to radiative-convective equilibrium (RCE) at grid spacings of 4 km, 1 km, and an LES grid spacing of 100 m. Parameterised convection was disabled, and the PBL scheme was disabled at LES resolution. The domain was a 20x20 km^2 patch of ocean with a constant sea surface temperature of 28 ºC, no Coriolis effect, constant radiative cooling (Herman and Kuang, 2013), and ideal evaporation (Chua et al., 2019). In the perturbation runs, constant anomalies to temperature and moisture tendencies were applied separately to two vertical levels (Kuang, 2010) at 412 hPa and 850 hPa. Perturbation runs were compared with control runs to view the differences in temperature and humidity profiles.

Negative and positive perturbations produced approximately symmetrical results, indicating linearity in model responses (Kuang, 2010). The LES perturbation responses are broadly similar to, but less smooth across the vertical profile than, results for a convection-resolving model (CRM) shown by Herman and Kuang, 2013. For perturbations at 850 hPa, the LES results resemble but are less smooth than results for some single-column models with parameterised convection in Hwong et al., 2021. Our responses show a prominent "kink" at about 650 hPa, approximately the freezing level, which is increasingly apparent as model resolution increases. The kink can be traced to the inclusion of ice in the microphysics scheme. The results show perturbation effects converging as model resolution increases, with 1 km results closer to those at LES resolution than 4 km results. Improved resolution decreases the smoothness of perturbation responses. Since our results are less smooth than CRM results previously used as a reference, the study shows that caution is required when comparing perturbation results to reference results which may be affected by model resolution and parameterisations. This study will contribute to benchmarks showing how convective schemes "should" react to small atmospheric perturbations, and help disentangle the effects of sub-grid parameterisations in numerical weather modelling.

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Keywords: *Model evaluation, linear responses, large eddy simulation*

Identifying observational errors in the calibration of hydrologic models: the reordering strategy

Xia Wu[a,b], **Lucy Marshall**[b] **and Ashish Sharma**[b]

[a] *College of Hydrology and Water Resources, Hohai University, Nanjing, 210098, China*
[b] *School of Civil and Environmental Engineering, University of New South Wales, Sydney, 2052, Australia*
Email: xiawu_hydrology@163.com

Abstract: Observational errors in input and output data are often ignored in the hydrologic model calibration, but this inevitable source of uncertainty can significantly impair parameter estimation. Decomposing observational errors from model residual errors is challenging as current methods are still limited by high dimensional computation or stochastic estimation errors. Based on the prior knowledge of data error distribution and their independence from the model calibration, this study attempts to overcome these limitations by transforming the direct value estimation of time-varying errors to the error rank estimation. A new algorithm, referred to as Bayesian error analysis with reordering (BEAR), is developed to realize the correspondence between the observational error rank and the residual error. The basic approach requires sampling errors from a pre-estimated error distribution and then reordering them with their inferred ranks via the secant method. The results of a synthetic case and a real case using the hydrologic models GR4J and HYMOD show several benefits of this new approach: 1) Applying the secant method can address the non-linear transform of a hydrological model from input errors to residual errors; 2) Compared with the stochastic error sampling, implementing the reordering strategy can improve the accuracy of observational error quantification, and consequently promote the parameter estimation; 3) Employing the Autoregressive model can deal with the persistence of hydrologic residual errors in calibration; 4) The delay between each input and its corresponding response can be explicitly acknowledged by decomposing the modelled hydrograph. The BEAR method is flexible and can be easily adapted to other environmental modeling studies with correlated or/and delayed responses. However, its ability is limited by the impacts of model structural error and the output observational error and their impacts will be discussed in this study.

Keywords: *Uncertainty quantification, input uncertainty, model calibration, autocorrelation, hydrologic model*

Delivering and applying the Pasture API to regional farming systems

N.I. Herrmann [a], P.J. Mitchell [b] and D.T. Thomas [c]

[a] *CSIRO Agriculture and Food, Canberra ACT 2601.*
[b] *CSIRO Agriculture and Food, Hobart Tasmania.*
[c] *CSIRO Agriculture and Food, Floreat, Western Australia*
Email: neville.herrmann@csiro.au

Abstract: The Pasture API software platform has been integrated with a public internet-based application called Farming Forecaster to provide seasonal forecasting information for grazing businesses in the temperate grazing regions of Australia. This new service demonstrates that complex simulation modelling is scalable and can deliver useful production insights for producers in an easily accessible and understandable manner.

The Pasture API (Thomas et al. 2019) was developed to encapsulate the GrazPlan pasture and ruminant models (GrassGro, Moore et al. 1997) into an automated workflow and associated published interface (Application Programming Interface - API). The Pasture API is configured to represent local farming conditions for a grazing enterprise at a location and produce modelled daily outputs and monthly forecasts in real-time. Third party applications can retrieve the data streams via the API and generate historical summaries and seasonal forecasts for grazing enterprises in temperate Australia. By combining the resulting streams of simulation data, a historical context for current and likely upcoming seasonal conditions can be determined. The seasonal forecast uses climatology over a period of 30 years of weather data for the specified location, considered to represent enough variability in climate to adequately explain future scenarios. In partnership with farming groups, local extension officers, consultants and web developers, a public web application called Farming Forecaster (https://farmingforecaster.com.au/) was developed. Farming Forecaster incorporates on-site soil moisture sensor data, climate data, climate predictions, and pasture production forecasts from the Pasture API. The NSW Hunter and the NSW South East are two NRM regions currently covered by this service and backed by Local Land Services support. The pasture forecasts are deployed for a nominated set of locations that capture variability in farming types and environment across each region. Currently, the Hunter region has 18 sites and the South East has 41.

Farming Forecaster displays historic, current and predicted field conditions that facilitate interpretation of seasonal trends and give more confidence in tactical decision-making. The pasture forecast is based on a representation of a typical set-stocked grazing enterprise at that location. It provides a simulated view with three-month forecasts for green herbage, plant available water, ground cover, animal condition and feed requirements. Concise text-based summaries of these forecast data are also presented.

The success of the integration of Pasture API and Farming Forecaster is partly indicated by the acceptance from the original Monaro and Southern Tablelands farming groups. From April 2020 to May 2021 there have been over 58,000 total page views on the web site (over 1000 per week). Other farming groups are actively seeking to join the list of supported locations. The seasonal forecasting facility in the Pasture API was previously only available to producers via GrassGro and required significant training to use effectively. The Farming Forecaster web site has demonstrated that sensor data and complex models can be delivered to producers and deliver effective decision support with significantly smaller levels of training.

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Keywords: *Pasture API, Farming Forecaster, GrassGro, GrazPlan, Senaps*

Preliminary results of parameterisation of DairyMod pasture model for tropical pasture; *Brachiaria*

J.M.P Jayasinghe [a b], **Daniel J. Donaghy** [a], **K. G. Pembleton** [c], **David G. Barber** [d] **and T. Ramilan** [a]

[a] *School of Agriculture and Environment, Massey University, Private Bag 11 222, Palmerston North 4440, New Zealand*
[b] *Department of Animal Science, Faculty of Animal Science and Export Agriculture, Uva Wellassa University, Badulla, 90000, Sri Lanka*
[c] *Centre for Sustainable Agricultural Systems and School of Sciences, University of Southern Queensland, Toowoomba, QLD 4350, Australia*
[d] *Queensland Department of Agriculture and Fisheries, Gatton Campus, Lawes, QLD 4343, Australia*
Email: P.Jayasinghe@massey.ac.nz

Abstract: Exploring improved tropical forages is considered to be an important approach in delivering quality and consistent feed options in tropical and even subtropical regions under changing climate scenarios. Pasture modelling has been an effective tool in simulating pasture growth and obviating expensive field research under a range of soil, climate, and management strategies. Many models lack parameters for tropical pasture species, hindering their use in tropical regions. This study aims to adapt the generic parameters in the DairyMod pasture model to parameterise and evaluate the model for the tropical pasture species *Brachiaria ruziziensis x B. decumbens x B. brizantha* 'Brachiaria Mulato II' (BM). Data were collected from plots of BM established at the Gatton Research Dairy (27° 54´S, 152°33`E), Queensland, Australia from 19 November 2020 to 06 May 2021 to parameterise the model. Model evaluation was performed through various statistical indices for accuracy and precision. Canopy structure and carbon partitioning, photosynthesis and respiration, senescence and leaf appearance parameters were mainly modified from the generic C_4 grass parameters in the model. Results showed that, species specific parameters setup for BM in the model simulated the total above ground yield (R^2=0.92), leaf (R^2=0.97), and LAI (R^2=0.93) at a reasonable accuracy. Stem production also ranged under acceptable level except for the second defoliation due to decreased cutting height. Despite these reasonable simulated results, the model tended to underestimate stem production. Reasons could be higher variation of residual weight across the seasons and model failure to explicitly capture the plant physiological changes like anthesis, accelerated growth rate and increased stem production associated with tropical pasture phenological developments. Results suggest that the developed BM parameters in DairyMod need further testing under range of locations and seasons to improve the model.

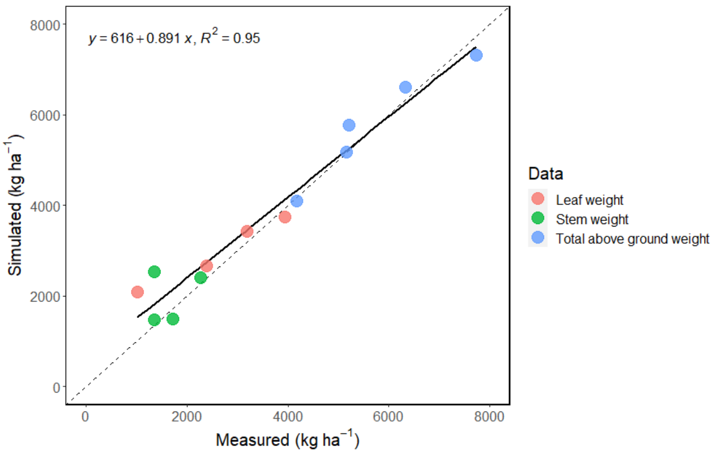

Figure 1. Relationship between measured and DairyMod simulated weights (total above ground, stem, and leaf) of Brachiaria Mulato II in Gatton Research Dairy, Queensland, Australia from December 2020 to May 2021

Keywords: *Brachiaria Mulato II, DairyMod, tropical pastures, simulation models*

Using GRASP to interpret soil and pasture nitrogen dynamics of subtropical sown pasture systems

Alice R. Melland[a], Jeffrey F. Clewett[a], Colin J. Paton[ab] and Jochen Eberhard[a]

[a] *Centre for Agricultural Engineering, University of Southern Queensland, Toowoomba, 4350, Australia*
[b] *EcoRich Grazing, Goombungee, 4354, Australia*
Email: alice.melland@usq.edu.au

Abstract: Nitrogen (N) constrains the water-limited productivity of subtropical pasture systems in Australia. Using the sown pastures version of the GRASP model and 60 years of weather data, Clewett et al. (2021) estimated the effects of pasture rundown on sown pasture and cattle productivity on lands retired from annual crop production in subtropical south-eastern Queensland. This paper highlights modifications to the GRASP model that were used to estimate effects of pasture rundown on productivity, key findings regarding N dynamics and opportunities for future research.

Rundown in pasture productivity because of immobilisation of N to soil organic matter typically occurs in sown pastures for several years after establishment. Rundown was modelled by defining the potential N uptake parameter (p99) as a variable dependent on pasture age during the pasture rundown phase with pastures on higher fertility soils ($p99 \geq 25$ kg/ha) having larger increases in initial productivity and taking longer for rundown to occur than on lower fertility soils ($p99 \leq 15$ kg/ha). Several key parameters controlling pasture growth rates (potential regrowth rate, transpiration efficiency and radiation use efficiency) were also treated as variables and calculated annually as linear functions of p99. This modified version of GRASP was calibrated using reported soil (Bennett et al. 2021), pasture and cattle (Melland et al. 2021, Paton et al. 2021) measurements from 18 sown pasture sites including the 5-year (2014-2018) Acland Grazing Trial. The trial had three paddocks rehabilitated to pasture in 2007, 2010 and 2012 after open-cut coal mining and one paddock sown on cultivated land in 2012. *Chloris gayana, Bothriochloa insculpta*, *Megathyrsus maximus, Dichanthium sericeum*, and winter-active legumes were the main species. The p99 parameter accounted for 64% of the variation in observed annual pasture growth that varied from 1 to 8 t/ha/yr with rehabilitated pastures performing as well as, or better than, pastures sown directly to cultivated land.

Swiftsynd and Botanal observations of pasture yield during the Acland Grazing Trial showed evidence of pasture yield rundown, particularly in the youngest pastures. This short-term lift and subsequent rundown in productivity enhanced the five-year mean annual estimates of pasture and cattle productivity during the trial period by up to 17% and 25% respectively above long-term "stable" levels of productivity. The duration of rundown was estimated to be longer (6.2 and 8.9 years) in the more fertile soils than in the less fertile soils (4.1 and 4.9 years). A constant value for minimum pasture leaf N percentage ($p101 = 0.46\%$) was retained in the modelling. However, rundown in pasture quality and N uptake was also observed in the field and suggests that values of p101 should also be reduced with pasture age. This warrants further investigation along with investigation of long-term changes in pasture composition due to rundown and any consequent changes in cattle production. The presence of annual legumes in the Acland trial paddocks was episodic and likely constrained by low plant-available P, and the GRASP module for growth of perennial legumes was therefore not used. However, use of both summer and winter-active legumes could improve pasture productivity so development of GRASP to more adequately represent legumes and their contribution to soil carbon and N cycles, pasture N uptake, pasture rundown, drought resilience and long-term carrying capacity would be useful.

The GRASP model was useful in assessing the productivity of sown pastures, including the effects of rundown. Further development of GRASP to more adequately represent legume-based pastures, soil N availability and changes in pasture quality is warranted. Such developments could better support decisions by managers of sown pastures and native pastures oversown with legumes.

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Keywords: *Cattle, pasture production, legume, mine rehabilitation*

Disentangling the effects of management and climate on perennial grass pastures and the degradation that follows multi-year droughts

J. Owens[a], **G. McKeon**[b] **P. O'Reagain**[c], **J. Carter**[b], **G. Fraser**[b], **B. Nelson**[c] **and J. Scanlan**[d]

[a]*Centre for Applied Climate Sciences, University of Southern Queensland, Toowoomba, Queensland*
[b]*Grazing Land Systems Group, Department of Environment and Science, Brisbane, Queensland*
[c]*Department of Agriculture and Fisheries, Charters Towers, Queensland*
[d]*Department of Agriculture and Fisheries, Toowoomba, Queensland*
Email: jo.owens@usq.edu.au

Abstract: Measured data from a long-term grazing trial and insights gained from modelling show that degradation processes following multi-year droughts are not easily reversed, and perennial pastures don't always recover. The combination of drought and overstocking has led to a significant decline in land and pasture condition, with the death of perennial grasses, loss of surface soil protection from ground cover and delayed recovery from drought. Tied up to the loss of desirable perennial grasses is the increase in non-desirable grasses and shrubs, which puts further pressure on the pasture resource available for grazing.

The aim of this study is to use a long-term, high-quality dataset to separate the effects of grazing management and climate on pastures using the biophysical model GRASP. The model captures the effects of both climate and grazing management on the pasture resource and pasture attributes. This involves gaining insights and detecting shifts in vegetation species composition after multi-year wet and dry periods, as well as how the grass species composition changes with the interaction of drought and high stocking rates. The loss of perennial, palatable and productive grass species is important for the grazing industry as it impacts pasture quality, quantity and resilience. When these grass species have been grazed out of the system, animal production can be impacted. The shifts in vegetation composition could also be driving changes in hydrology through reduced infiltration, increased runoff and changed water use patterns by vegetation.

The Wambiana grazing trial is regarded as one of the most important field experiments in grazing science because it addresses the major issue of long-term livestock grazing of Queensland's native pastures in a highly variable climate. The trial provides an excellent opportunity to evaluate the effects of climatic (i.e. multi-year wet and dry periods) and grazing management (i.e. fire and stocking rate) on pasture production and resource degradation for a savanna ecosystem (open woodland with perennial native pastures). The simulation study used the GRASP model to represent various processes affected by: a) rainfall variability at multi-year timescales with periods of above average rainfall (Wet Periods 1 and 2) and below average rainfall (Dry Periods 1 and 2); and b) variation in grazing pressure by comparing moderate and heavy continuous stocking rates.

Combining data on stocking rates, field measurements of runoff, pasture growth, biomass, grass basal area, species composition and satellite remote sensed green and dry fractional cover with the GRASP model provides the opportunity for high quality model parameterisation where many of the model parameters are strongly constrained by observational data and previous modelling experience. A well calibrated model is a starting point to investigate the development of new model functions and analyses. We detail how the model calibration was developed, and to what extent we could explain the observed changes in pasture biomass. This work revealed emerging processes in the landscape that we do not currently model, some of which are caused by prolonged droughts and high stocking rates. These processes include the increase in introduced grass species *Bothriochloa pertusa* and an increase in the native shrub currant bush (of up to 30% of the land surface area). This work also revealed the need to model the effects of degradation of soils (surface sealing and reduced infiltration) that followed multi-year drought and high utilisation rates. The parameters and insights derived from this study will help inform the modelling of degradation and recovery in grazing landscapes. This study is important for the grazing industry and policy as it impacts on calculations of long-term carrying capacities, pasture biomass and ground cover for sustainable grazing. This study contributes to current applications of GRASP addressing long-term carrying capacity in areas with woody vegetation.

Keywords: *Drought, recovery, woody vegetation, savanna ecosystems, parameter estimation*

Modelling grassland foliage phenology responses to soil water availability

Jinyan Yang[a], Belinda E. Medlyn[a], Craig V. M. Barton[a], Amber C. Churchill[a,b], Martin G. De Kauwe[c], Mingkai Jiang[a], Arjunan Krishnananthaselvan[a], David T. Tissue[a], Elise Pendall[a] and Sally A. Power[a]

[a] Hawkesbury Institute for the Environment, Western Sydney University, Penrith, NSW, 2750, Australia
[b] Department of Ecology, Evolution and Behavior, University of Minnesota, St. Paul, MN, USA
[c] School of Biological Sciences, University of Bristol, Bristol, BS8 1TQ, UK
Email: Jinyan.Yang@westernsydney.edu.au

Abstract: Climate change is expected to bring greater variability in the amount and frequency of rainfall. Grassland productivity is strongly affected by rainfall variability, mainly via the timing and rate of foliage growth and senescence. In current land surface models, the impact of rainfall is accounted for by soil moisture availability (SWA). While growth generally follows SWA in most models, as a result of photosynthesis and allocation responses to SWA, the impacts of SWA on senescence are generally unaccounted for. The impacts of SWA on senescence are challenging to model due to the complexity of the plant hydraulic regulation and numerous parameters that are difficult to measure *in situ.*

We thus used a parsimonious function (i.e., beta function), which has only one parameter to control the nonlinearity of the response of senescence to soil moisture availability. We first implemented the beta function into an empirical grassland phenology model. The parameter values of the model were obtained by fitting it to ground-based cover observations in rainfall manipulation field experiments and grassland monitoring sites in western Sydney, NSW. The obtained parameter values were then used to drive a land surface model implemented with a beta function (GDAY). GDAY was subsequently evaluated at three independent flux tower sites against measured evapotranspiration and satellite-based cover.

The evaluation suggests that the beta function performed better than existing grassland models (Choler et al. 2010; De Kauwe et al. 2017; Johnson et al. 2003) that do not appropriately represent soil moisture impacts on senescence. The beta function thus is a useful and practical solution for representing the impacts of SWA on senescence in land surface and pasture models. This work presents new ways to account for rainfall variability on grassland phenology which has direct impacts on productivity and future climate projection.

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Keywords: *Grassland phenology and productivity, climate change, water availability, Senescence*

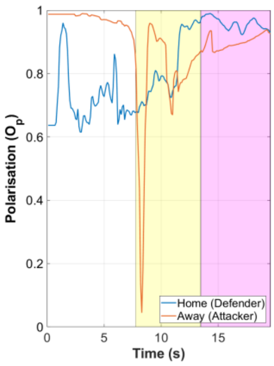
Collective states in sub-elite female rugby 7s: A case study on two plays

H.F. Koudela[a], T.M. Schaerf[a], T. Lathlean[b], A.J. Murphy[c] and M.C. Welch[a]

[a]*University of New England* [b]*University of Adelaide and Flinders University* [c]*University of Notre Dame Australia*
Email: hkoudela@myune.edu.au

Abstract: Moving animal groups display the capability to perform highly coordinated manoeuvres without a centralized control. Familiar examples from nature that have been studied extensively include flocking behaviour 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 behaviour. 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 behaviour exhibited in experimental data. 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 state of group collective motion can be quantified through the use of metrics such as group centroid, measures of group polarisation and rotation. Figure 1 shows an exemplar time series of polarisation for two teams (background colours indicate phases of play) and the movement of the field (The circles indicate the end points of the trails) when the polarisation of the away team drops dramatically, indicating a change in the collective state of the team. This collective state change reflects a shift in game-play that resulted in some team members reacting with rapid changes in direction

Two segments of gameplay were selected for analysis; one in which in the attacking team was successful (Play 1) and one which the attack was unsuccessful (Play 2). Player positions for both teams were recorded semi-autonomously using the Channel and Spatial Reliability Tracker (CSRT) algorithm implemented in OpenCV. Location was recorded every 3 frames from 30 fps video resulting in 222 records for play 1 and 624 records for play 2.The positions were then converted into a meter based coordinate system using 4 homography matrices dividing the field based on the position of the camera and the approximate apex of the fields curve. To account for pixel errors a search of the neighbourhood of each recorded reference point was used to reduce the error in a set of training points. The error was then measured using a set of testing points. This project calculates statistical measures that characterise collective states, group structure and their differences across phases of play. The goal of this research is to understand the relationship between these measures and successful/unsuccessful actions within gameplay. The analysis of collective movements will also be used to create agent-based simulations based upon the interaction rules that emerge, providing a valuable tool that will allow coaching staff to understand the effects of individual-level interactions on the outcomes within game play.



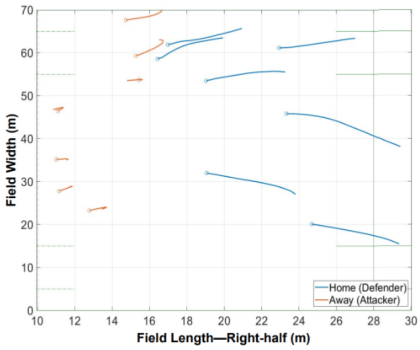


Figure 1. (left) Polarisation (O_p) of both teams over time for the successful Play, colours show three gameplay phases: regular play (white) multiplayer passing (yellow) and breakaway (magenta), and (right) the paths of players on the field during the drop in Attacks Polarisation

Keywords: *Collective motion, field sport, movement patterns*

Agent-Based Modelling to study the interactions in decision-making between environmental water managers, irrigators and water supply authorities in the Goulburn River catchment

Lubna Meempatta[a], J Angus Webb[a], Avril C Horne[a] and Michael J Stewardson[a]

[a] *Water, Environment and Agriculture Program, Department of Infrastructure Engineering, Faculty of Engineering and IT, The University of Melbourne, Melbourne, Australia*
Email: lmeempatta@student.unimelb.edu.au

Abstract: When consumptive and conservative water users depend on common-pool resources, conflicts arise regarding when and how much water each party receives. In many cases, the decisions on water allocation are bounded by legal and regulatory frameworks, but there are instances where water users will have to modify their demands according to the changes in the environment and other users' behavior. For example, the ability to deliver environmental water outcomes hinges on the decisions and delivery of irrigation water, especially during periods of peak irrigation demand. Understanding these complex interactions between different actors in a water resource system will inform improved policy instruments for water resource allocation.

Historically, environmental water has been allocated as minimum passing flow in most river basins, and hence environmental water has been modelled as a constraint in water resource models. Now, there is a growing trend for active environmental water management (deliberate releases of water at different times and of different volumes) to obtain better environmental outcomes. Agent-Based Modelling (ABM) is a promising way to represent active environmental water decision-making by allowing autonomy for water users to make changes to their demand depending on the decision-making behaviour of other actors, and allowing them to influence other actors in their decision making. While there are ABM studies available on irrigator decision-making regarding crop choice, water use decisions and how they cooperate (or conflict) with other agents (mainly other irrigators), studies on environmental water managers and water supply authorities (WSAs) as agents in an ABM setting are very limited. Where they are considered as agents, their role is limited to imposing restrictions on the water quality to an acceptable level, and to press for new regulations to restrict irrigators' allocation (e.g., Akhbari and Grigg, 2013).

This paper explores the capability of an Agent-Based Model to represent the interactions among two key water user groups in the Goulburn catchment – irrigators and environmental water managers, and to model their interaction with the decisions of the water supply authority. The environmental and irrigator agents are modelled as water users with different demand patterns, and the model allows them to update their demand pattern based on the environmental conditions, outcome of their past decisions, and the decisions by other users. The water supply authority agent in the model can strategically allocate the resources based on the previous water delivery outcome for each water user group. The model is expected to demonstrate the impact of varying degrees of water allocation on irrigators and environmental water. The model is built on the source code of Aqua.MORE software (Agent-based MOdelling of REsources in Socio-Hydrological Systems) developed by Huber et al. (2019).

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Keywords: *Agent-Based Model, water resource allocation, decision-making, Goulburn River Catchment*

Correlates between inferred rules of interaction and group-level statistics of collective motion in small shoals of fish under different predator threat scenarios

Timothy M. Schaerf [a], **Alexander D. M. Wilson** [b, c], **Mitchell Welch** [a] **and Ashley J. W. Ward** [c]

[a] *School of Science and Technology, University of New England, Armidale NSW, 2351, Australia*
[b] *School of Biological and Marine Sciences, University of Plymouth, Devon PL4 8AA, United Kingdom*
[c] *School of Life and Environmental Sciences, University of Sydney, Sydney NSW, 2006, Australia*

Abstract: Many species exhibit remarkable displays of coordinated collective motion. The broad hypothesis underpinning the theory of collective motion is that group-level patterns of movement emerge due to repeated interactions between individuals; these interactions are sometimes referred to as rules of interaction. Support for this hypothesis comes from a wide range of model-based studies of collective motion. Within the models, rules of interaction dictate how individuals adjust their velocity as a function of the relative positions and velocities of other members of the group. The rules of interaction usually include at least one of the following: (1) a rule for collision avoidance with neighbouring group members at short-range (a repulsion interaction); (2) a rule for aligning direction of motion with group members at intermediate distances (an orientation interaction); (3) a rule for moving toward group members at intermediate to longer distances (an attraction interaction). Adjusting the ranges over which repulsion, orientation and attraction interactions apply can affect emergent group-level patterns of movement, including the formation of swarms, mills, parallel movements and group fragmentation (Couzin et al. 2002, D'Orsogna et al. 2006).

Over the last decade researchers have developed methods for inferring rules of interaction directly from experimentally derived trajectory data, including force-mapping (Herbert-Read et al. 2011). In its simplest form, force-mapping determines the mean changes in the components of velocity of individuals as a function of the relative coordinates of other group members. The force-mapping approach is reasonable at extracting the qualitative, and sometimes the quantitative, form of repulsion and attraction interactions, but is subject to inaccuracies relating to group patterns of movement and group size (Mudaliar and Schaerf, 2020).

Given that methods for inferring rules of interaction are relatively new, most experimental studies that have used these techniques have examined behaviour in a single ecological context. Here, we examine how rules of interaction inferred via force-mapping and measures of group order covary in response to varying threat scenarios experienced by small shoals of eastern mosquitofish (*Gambusia holbrooki*) in the presence of a sympatric predator, a jade perch (*Scortum barcoo*). Under most treatments examined, the underlying rules for how the mosquitofish adjusted their speed and heading remained qualitatively similar, with individuals moderating their velocity consistent with collision avoidance at short range and attraction to neighbouring group members at longer distances. However, when the predator was present in the experimental aquaria, and had not been recently fed, the qualitative form of the rules of interaction changed dramatically, including a tendency for rapid acceleration in response to near neighbours in any direction. In concert with changes in detail of the rules of interaction, measures of grouping, including the persistence of subgroups, and the emergent patterns of motion also varied. This study illustrates how ecological context, in this case the details of the presence of a predator, affects both rules of interaction and group-level patterns of movement.

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Keywords: *Collective motion, rules of interaction, force-mapping, collective order, Gambusia holbrooki*

Patterns of information transfer within collective movement simulation: Applications to sport

Mitchell Welch[a] and **Timothy Schaerf**[a]

[a] *School of Science and Technology, University of New England, Armidale, 2351, Australia*
Email: mwelch8@une.edu.au

Abstract: Collective movements are 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. Self-organisation and collective movement can be observed in humans within formations exhibited in field sports such as football and rugby. Existing studies have (1) provided strong evidence of both self-organisation amongst movements and interactions of individuals within teams and between members of opposing teams, and (2) demonstrated that teams (as a group of individuals) form collective states that range from un-ordered swarm-like formations through to highly polarised groups that move with high alignment as they engage in play (Welch, Schaerf et al. 2021).

Information transfer plays a key role in collective movement, allowing for synchronisation and collective decision making related to resource gathering and the sensing/avoidance of predators or similar dangers. Information is transferred within a group by the means of the individuals constantly sharing directional formation. Individuals update their headings based upon the detected directionality of (at least) a subset of neighbours within the group. Information transfer can be analysed in this context by measuring the time-delay of correlations across directional changes in a pair-wise fashion between individuals. This provides an indication of the direction of information flow and the effectiveness of the transfer.

In this research, we apply these analysis techniques to some simple simulated scenarios to understand the nature of information transfer with regards to interactions amongst individuals. The initial simulation places individuals on fixed-tracks with formations that reflect those seen in playing formations in soccer. Time delays are applied to each individual's track designed to force the expected pair-wise directional correlation delays. Subsequent simulations relax the use of fixed tracks by introducing interaction rules adapted from a zonal collective movement model. This allows for sensitivity analysis of information transfer across different interaction ranges. The outcomes of the simulation are assessed against a data-driven analysis of movement soccer of soccer players during ordered, highly polarised, phases of play. Openly available datasets from two sub-elite soccer games comprising of player movement traces obtained using a time-of-flight radio tracking system were analysed. This data was annotated to indicate offensive, defensive out-of-play phases using synchronised video recordings of each match. An order parameter for group polarisation (O_p) was calculated and used to classify the sequences of play as ordered ($O_p > 0.65$) or not. The pair-wise directional correlation delays for each combination of players across each polar segments were analysed for comparison with those extracted from the simulations.

Early results indicate that the directional correlation delay tends to increase with distance between players, however further analysis is underway with the aim of understanding the nature of the information transfer and how the mechanics the individual players ability to perceive directional changes among neighbours affects the formation.

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Keywords: *Collective movement, information transfer, self-organisation*

Carbon Farming Optimiser: application to grazing systems in SE Australia

Oscar J. Cacho [a], **Aaron Simmons** [a,b] **and Cathleen Waters** [c]

[a] UNE Business School, University of New England, Armidale, 2351, Australia, [b] NSW Department of Primary Industries, Taree, 2430, [c]NSW Department of Primary Industries, Dubbo
Email: ocacho@une.edu.au

Abstract: The Carbon Farming Optimiser (CFO) takes inputs related to a mixed farming system and generates a multi-period linear programming (MPLP) model to maximise profit, subject to resource constraints, over a given planning horizon. The model, written in MATLAB, is designed to simplify the process of creating the large matrices required for optimisation over several decades, and processing large volumes of results, while maintaining a realistic representation of a farming system. The innovative aspect of the model is in the matrix generator and the data structures that represent the components of the farm.

The MPLP model generated by the CFO has the standard structure, where the problem is to select the sequence of activities through time ($\mathbf{x}_t$) that maximises the objective function $f(\mathbf{x}_t)$ subject to a set of constraints $\mathbf{A}\mathbf{x}_t \leq \mathbf{b}$, where $\mathbf{A}$ is a matrix of technical coefficients and $\mathbf{b}$ is a vector of resource constraints. The objective function in this case is net present value (NPV) over a planning period of T years, but this can be changed within the model if required. Besides the typical resource constraints of land, labour and capital available on the farm, additional constraints account for greenhouse gas emissions and sequestration. The model was applied to a farm operating under the Emissions Reduction Fund (ERF) of the Australian Government.

In this example, the CFO was used to optimise a cattle-breeding enterprise located on the mid-north coast of NSW for NPV over a 30-year period. The property was mapped into three production zones using GIS – low, moderate and high. Low and moderate productivity zones were dominated by native pastures and the high productivity zone was dominated by naturalised pastures, each with an area of 859, 622 and 1151 ha, respectively. The CFO could select either cattle production or earning C credits through woody revegetation for the low production zone and naturalised or improved pastures for the high productivity zone. No changes were available for the moderate production zone. Gross margins (GM) for cattle breeding on native, naturalised and for revegetation were developed in collaboration with the land manager. C emissions associated with cattle production or sequestration estimates associated with revegetation were consistent with the National

Greenhouse Gas Inventory and ERF. The optimisation was carried out at carbon prices in the range \$0 - \$14 tonne CO_2^{-1}, labour was constrained to three full-time workers and annual capital was constrained to \$150 000 per year.

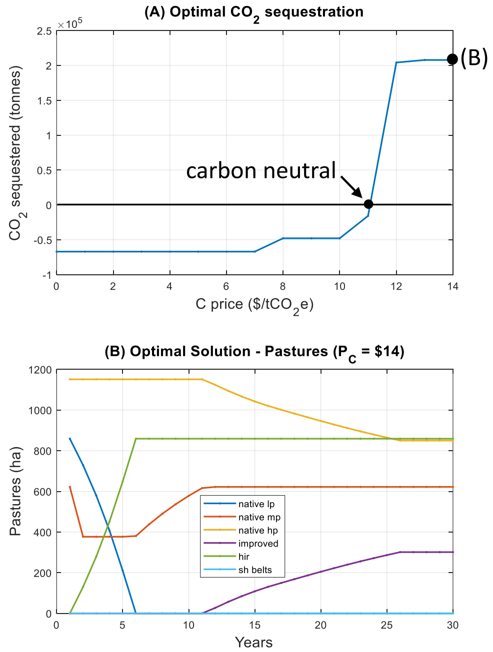

Figure 1. Optimisation results for sample farm.

Based on these assumptions, the farm could become carbon neutral at a price of ~\$11 tonne CO_2^{-1} (Figure 1A) while maximising profits over 30 years. Behind the solution for each C price there is an optimal land-use mix. Under the high C price of \$14, NPV was maximised by investing all capital into fencing off low productivity areas to earn C credits in the first few years, and investing this capital into converting ~ 800 ha of high productivity areas to improved pastures from year 11 (Figure 1B). The model is flexible and can be applied to other properties and scenarios.

Keywords: *Carbon markets, multi-period linear programming, climate abatement*

EXTENDED ABSTRACT ONLY

A decision support tool for environmental impact assessment in mariculture: An integrated modelling approach

G. Gunaratne[a], **H. Carmody**[a], **J. Crisp**[a], **E. McCall**[a] **and L. Bruce**[a,b]

[a] *BMT Commercial Australia, Brisbane, AUSTRALIA*
[b] *The University of Western Australia, Perth, AUSTRALIA*
Email: gayan.gunaratne@bmtglobal.com

Abstract: Rapid growth of aquaculture over the past few decades reached 82 million tonnes in 2018, of which production from mariculture (marine based aquaculture) represents 38% (FAO, 2020). When scoping dedicated aquaculture development zones (ADZs), an environmental impact assessment (EIA) is used to ensure that standing biomass from planned farms fall within the site's ecological carrying capacity (ECC). For mariculture, ECC is substantially affected by fish faeces and uneaten feed accumulation on the seabed and related water quality degradation. In order to determine a sustainable solution, integrated aquaculture modelling (Bruce *et al*, 2019) has become a necessary component of EIAs to determine an appropriate ECC. In this study, we present a decision support tool developed to support ADZ EIAs using modules from the TUFLOW FV software (2021). The tool has been designed to aid in site selection and determine a farm based sustainable carrying capacity within proposed ADZs. After application for use in different geographical regions in Australia, Europe and the Middle-East, an in-depth analysis of modelling approaches, refinement of workflows and methods was carried out to develop an integrated model framework to select ADZs for mariculture (Figure 1).

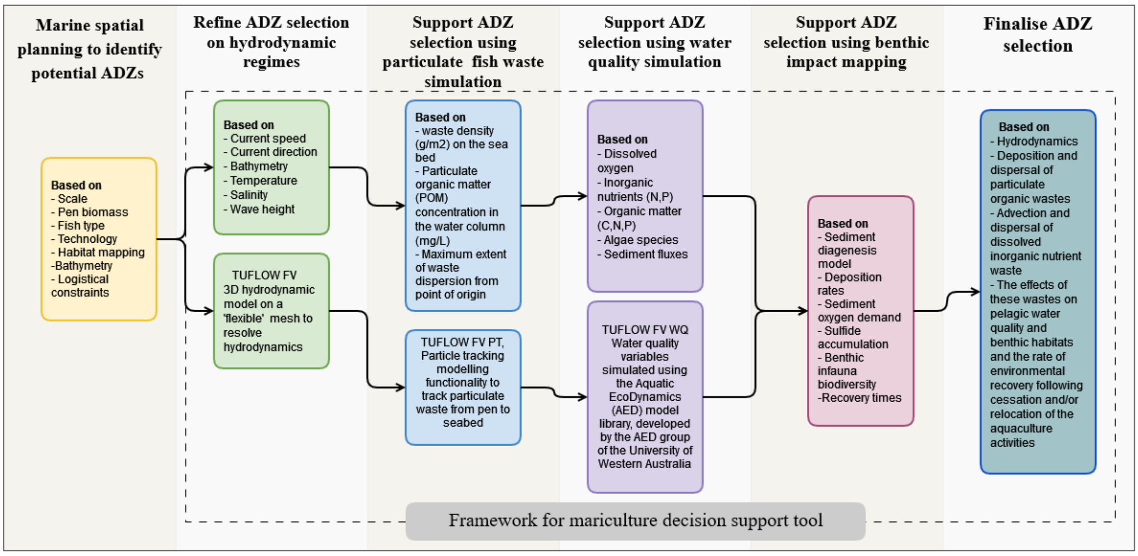

Figure 1. Integrated model framework to support environmental impacts of aquaculture development zones (ADZs) for assessment of mariculture using TUFLOW FV (2021) software

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Keywords: *Mariculture, ecological carrying capacity, TUFLOW FV, environmental modelling*

Performance of the APSIM Classic-Wheat yield prediction: a review and meta-analysis

Shirui Hao[a], **Dongryeol Ryu**[a], **Andrew W Western**[a], **Eileen Perry**[b,a], **Heye Bogena**[c] **and Harrie Jan Hendricks Franssen**[c]

[a] *Department of Infrastructure Engineering, Faculty of Engineering and Information Technology, The University of Melbourne*
[b] *Agriculture Victoria, Department of Jobs, Precincts and Regions*
[c] *Institute of Bio- and Geosciences, Agrosphere Institute (IBG-3), Forschungszentrum Jülich*
Email: shiruih@student.unimelb.edu.au

Abstract: Process-based crop models are widely used to simulate crop growth, guide cropping practices, evaluate environmental impacts, and seek solutions to boost crop production. The Agricultural Production Systems SIMulator (APSIM) (Holzworth et al., 2014) is an extensively adopted crop model that can simulate growth for various crops under a range of user-specified environmental conditions (e.g., air temperature, soil water, soil nutrients, etc.). This work reviews the performance of APSIM Classic (version 1.X – version 7.9) wheat yield prediction under different conditions and explores the influential factors affecting performance (Hao et al., 2021).

In this research we reviewed 76 published works utilising APSIM wheat, from September 1997 to February 2020 across thirteen countries. We collated and used independent evaluation datasets of APSIM-Wheat yield prediction using field level *in situ* data. The locations of the published studies were primarily in Australia (41 studies) and China (20 studies), as APSIM wheat is used more commonly in these countries. Thirty of the 76 studies that had evaluation data extractable from the published paper or were provided by the authors were collected for the meta-analysis. The modelled and observed grain yields from these studies was compared to identify factors that influence the model performance. The coefficient of determination (R^2), root mean squared error (*RMSE*), and normalised RMSE (*NRMSE*) were used in quantifying performance.

Overall, APSIM-Wheat predicted yield with R^2= 0.68, *RMSE* = 1.06 t/ha, *NRMSE* = 28.89%, covering a wide range of conditions. The model performance improved markedly with site-specific calibration, with R^2= 0.90, *RMSE* = 0.64 t/ha, *NRMSE* = 14.08%. Site specific calibration included (1) cultivar parameter tuning to observations and/or (2) soil texture, soil hydraulic, and/or soil chemical parameters were specified with field measurements. If none of these conditions were satisfied due to limited modelling information, the model prediction accuracy was lower, with an R^2 of 0.58, *RMSE* increasing to 1.25 t/ha, and *NRMSE* of 32.46%. Lower model accuracy was also found under unfavourable environmental conditions. APSIM-Wheat showed greater uncertainties where crops were grown under water or nitrogen limited conditions, with a tendency to overestimate yield for water stress and underestimate yield for nitrogen limitation. The model also tended to overestimate crop yield under conditions of heat wave or frost damage. Other factors such as soil cracking, lodging, and plant diseases are also influential factors affecting the model performance. Overall, the results from our analysis indicated that greater model prediction uncertainty is associated with crops grown under stressed conditions and with no or limited calibration processes.

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Keywords: *APSIM Classic, wheat, yield prediction performance, meta-analysis, literature review*

Modelling the benefits of using genomic tools to inform herd management decisions

Adam C. Liedloff [a], **Alison Laing** [b], **Sabine Schmoelzl** [c], **Brad Hine** [c], **Toni Reverter-Gomez** [b] **and Laercio Porto Neto** [b]

[a] *CSIRO Land and Water, Darwin, 0822, Australia,* [b] *CSIRO Agriculture and Food, St Lucia, 0822, Australia,* [c] *CSIRO Agriculture and Food, Armidale, 2350, Australia*
Email: adam.liedloff@csiro.au

Abstract: Loss of improved herd genetics when livestock producers are forced to drastically destock in response to drought can have major economic impacts for farm businesses. Commercially available genomic tools now provide a measure of the genetic value of individuals in the herd, allowing genetic merit to be considered when selecting animals to sell, however estimates of the long-term economic costs/benefits of destocking based on the traditional pregnancy status and age versus the genetic merit of individual animals are not currently known.

We used simulation modelling to help Australian producers identify likely optimal destocking and restocking strategies during drought events by allowing genetic merit to be considered. To address questions of genetic merit the model needed to be able to simulate the whole farm system, represent herd dynamics of individuals grazing on native pasture, provide all required herd management activities, track farm economics, as well as include a genetic index of individuals in the herd with inheritance considered during mating.

The Crop Livestock Enterprise Model (CLEM) was used in this study. This whole-farm model was built with many of this study's requirements already considered, and the individual-based herd sub-model was enhanced to track the genetic indexes of individuals and consider these when performing herd management activities including drought-induced selling.

This presentation describes the functionality of the CLEM model using a case study property defined in conjunction with Angus Australia where the commercial genomic test (HeiferSelect) was used to predict the generic merit and value of individuals across the herd. A range of industry-relevant destocking scenarios were considered to investigate the real-world economics of the scenarios. Over the long-term, these simulations support farmers and industry groups by informing their decision making to enable them to meet the challenges imposed by an increasingly variable production environment.

Keywords: *Cattle grazing, CLEM, Crop Livestock Enterprise Model, drought, genetics*

A simulation of greenhouse gas emissions intensity of high and low productivity sheep grazing systems

Malcolm McPhee [a], Clare Edwards [b], Steven Harden [c], Chris Guppy [d], Travis Naylor [e], Frances Phillips [e] and Roger Hegarty [d]

[a] NSW Department of Primary Industries, Livestock Industries Centre, Armidale 2351, Australia, [b] Central Tablelands Local Land Services, Mudgee 2850, Australia, [c] NSW Department of Primary Industries, Tamworth Agricultural Institute, Calala 2340, Australia, [d] School of Environmental and Rural Science, University of New England, Armidale 2351, Australia, [e] Centre for Atmospheric Chemistry, University of Wollongong, Wollongong 2522, Australia
Email: malcolm.mcphee@dpi.nsw.gov.au

Abstract: Agricultural production impacts the environment through greenhouse gas (GHG) emissions of methane (CH_4) and nitrous oxide (N_2O). The consequences of emitting GHG emissions from grazing ruminants and intensification of production are important industry issues that need addressing. In Australia, New Zealand and Europe, there is a focus on reducing both total CH_4 and N_2O and the emissions intensity (EI, kg CO_2e/ kg lamb and wool production). The objectives of this study were to quantify the annual variation in the long-term effects of intensification on GHG emissions and EI of sheep production occurring in low and high productivity grazing systems (PGS).

A 30-year simulation was conducted using the GrassGro® (Moore et al., 1997) decision support tool with initial parameter values of soil, pasture and production data drawn from a research trial. The simulated results are compared to experimental data of observed liveweight (LW) for both ewe and wether lambs and CH_4 production for ewes and lambs using Open Path Fourier Transformed Infrared (OP-FTIR) spectroscopy.

The root mean square error between mean observed and GrassGro® estimated LW for both ewe and wether lambs (n = 12) was 1.19 and 1.45 kg for high and low PGS, respectively. Observed 24-hour CH_4 production, using OP-FTIR spectrometers, across 5 days (means ± SE), of 17.2 ± 0.51 and 21.3 ± 0.70 g CH_4/day were lower than the mean GrassGro® CH_4 estimates (n =30) of 19.8 ± 0.39 and 26.6 ± 0.10 g CH_4/day for high and low PGS, respectively. The long-term simulated means ± SD (n = 30) for CH_4 were 1869 ± 134 and 1076 ± 63 kg CO_2e/ha/year and for N_2O were 596 ± 61 and 318 ± 28 kg CO_2e/ha/year for high and low PGS, respectively. There was a 14% lower long-term EI, based on simulated means across 30 years, on the high PGS with a median EI ± SD of 10.2 ± 1.3 and 11.8 ± 1.6 kg CO_2e/kg lamb and wool production for high and low PGS, respectively (Figure 1). The lower EI but higher yearly CH_4 and N_2O emissions on the high PGS shows the potential for intensification to reduce the emissions footprint of food but highlights the importance of the metric used to quantify emissions.

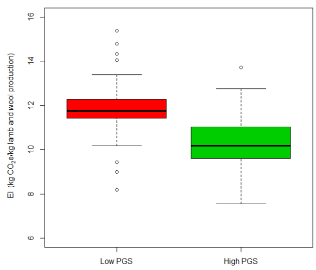

Figure 1. Simulated estimates of emissions intensity (EI; CO2e/kg lamb and wool production) for low and high productivity grazing systems (PGS) modelled over 30 years (1 September 1981 to 31 August 2011).

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Keywords: *GrassGro, methane emissions, nitrous oxide emissions*

Random forest classification: A case study of dryland crop cover mapping in the Victorian Mallee using Sentinel-2A, Sentinel-3, and MODIS imagery

S. Sabaghy [a], **K.J. Sheffield** [a], **and S.A. Robson** [b]

[a] *Agriculture Victoria Research, Department of Jobs, Precincts and Regions, AgriBio, 5 Ring Road, Bundoora, 3083, Victoria, Australia*
[b] *Agriculture Victoria Research, Department of Jobs, Precincts and Regions, 110 Natimuk Rd, Horsham, 3400, Victoria, Australia*
Email: sabah.sabaghy@ecodev.vic.gov.au

Abstract: Land cover characterises the land surface, which is fundamental information for wind and water erosion management. Of particular interest are different crop types since different crop residues provide different levels of protection against wind or water erosion and have different risk characteristics. This study examines the use of random forest algorithm for accurate crop classification across the Victorian Mallee to support wind erosion risk monitoring activities. The random forest is one of the most popular and efficient machine learning algorithms for land cover classification.

The Mallee is an economic region located in north-west Victoria and covers a total area of approximately 40,000 km^2. It is characterized by flat lands and low-lying areas. The dominant light sandy top-soils, low annual rainfall and characteristic strong winds makes the Mallee one of the most vulnerable areas to wind erosion in Australia. Wind erosion assessment by the National Landcare Program (NLP) identified that 97% of the Mallee Management Unit's dryland cropping areas and 81% of its grazing areas are highly or moderately impacted by wind erosion. This represents the third and second highest figures respectively when compared to all other Australian Natural Resource Management (NRM) regions.

This study initially used a single date MODIS image - a freely available satellite imagery - for land cover mapping. However, as the MODIS satellite platform approaches mission end, the study also investigated alternative multispectral images including Sentinel-2A and Sentinel-3 synergy data for land cover mapping with the aim to compare different platforms and identify the most promising satellite(s) data for crop cover type classification.

The use of random forest algorithm for crop type classification indicated satisfactory overall accuracy (greater than 90%) and kappa coefficient (greater than 0.80). The MODIS-based land cover map performed the best, with an overall accuracy of 97.9% and a kappa coefficient of 0.96. A kappa value close to 1 assures a strong agreement between classified image and reference data. The second-best classification accuracy was achieved for the Sentinel-3 synergy-based land cover map which reached an overall accuracy of 94.2% and kappa value 0f 0.88. These results show the potential of Sentinel-3 synergy imagery in deriving representative spatial variability of land cover.

In this study, the random forest was trained to assign a discrete land cover to each pixel. Future work could expand this research is to develop and test random forest model/s that can classify mixed pixels. This paper focuses on imagery acquired during 2019, future work will apply these techniques to imagery in other years to assess the robustness of this approach. Assessment of these techniques across different crop growing regions will further ascertain the usefulness of random forest classification of land cover in different climatic zones and growing regions.

Keywords: *Crop cover mapping, image classification, random forest, machine learning, agriculture*

Considering unknown uncertainty in imperfect models: nitrogen mineralization as a case study

Maria P. Vilas[a], **Frederick R. Bennett**[b], **Kirsten Verburg**[c] **and Matthew P. Adams**[d,e]

[a] *Department of Resources, Queensland Government, Brisbane QLD Australia*
[b]*Department of Environmental Science, Queensland Government, Brisbane QLD Australia*
[c]*CSIRO Agriculture and Food, Canberra ACT Australia*
[d]*School of Mathematical Sciences, ARC Centre of Excellence for Mathematical and Statistical Frontiers, and the Centre for Data Science, Queensland University of Technology, Brisbane QLD Australia*
[e]*School of Chemical Engineering, The University of Queensland, St Lucia QLD Australia*
Email: maria.delapazvilas@resources.qld.gov.au

Abstract: All models are imperfect, so it is important to consider uncertainty in their predictions. When calibrating models to measured data, uncertainty in the model can be simultaneously estimated, although there are multiple methods available for doing this. In this study, we applied ensemble smoothers and Bayesian inference to calibrate a model of nitrogen mineralization in soils. We obtained mineralization measurements from a previously published study that measured changes in inorganic nitrogen over long-term laboratory incubations in a soil located in the Mackay Whitsundays region (North Queensland). Simulations were performed using the Agricultural Production Systems Simulator (APSIM). We inferred two parameters that characterize the size of the simulated soil organic carbon pools (fbiom and finert) because it is difficult to estimate these parameters from measurements only. For the calibration, we considered two different sources of uncertainty: measurement noise and noise of unknown origin, the latter of which includes all non-measurement related errors. We found that ignoring noise of unknown origin can result in an overly optimistic representation of the model error (Figure 1a,c). On the contrary, incorporating noise of unknown origin can lead to a more accurate representation of the uncertainty in the predictions, with model predictions providing adequate coverage of measurements (Figure 1b,d). We show that parameterizing fbiom and finert is difficult because these parameters are correlated, hence different combinations of parameters can equally well simulate the measured data. We suggest that future work needs to provide a means of parameterizing at least one of these fractions independently to facilitate parameter identifiability.

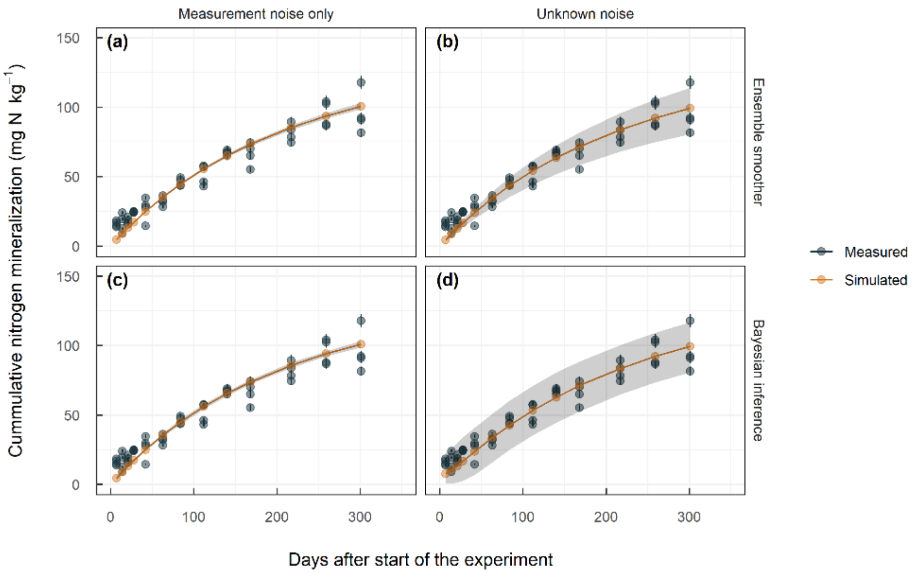

Figure 1. Measured (grey dots) and simulated (orange lines) nitrogen mineralization (mg N kg^{-1}) for the ensemble smoother with multiple data assimilation (ES-MDA) (a), flexible iterative ES-MDA (b), Bayesian inference with measurement noise only (c), Bayesian inference with measurement noise and additional noise (d). The error bars in the measured data represent the error of the laboratory method. Shaded areas represent the predicted 95% credible intervals.

Keywords: *Soil nitrogen, mineralization, Sequential Monte Carlo, ensemble smoothers, APSIM*

Hungry hungry hoppers: multidimensional modelling of masticating morphs

F Georgiou [a], **N Thamwattana** [a], **B Lamichhane** [a], **J Buhl** [b] **and JEF Green** [c]

[a] *School of Mathematical and Physical Sciences, University of Newcastle, Callaghan, 2308, Australia*
[b] *School of Agriculture, Food and Wine, University of Adelaide, Urrbrae, 5064, Australia*
[c] *School of Mathematical Sciences, University of Adelaide, Adelaide, 5005, Australia*
Email: fillipe.georgiou@uon.edu.au

Abstract: Density dependent phase polyphenism is the exhibiting of two or more distinct phenotype expressions from a single genotype depending on local population density. The most well known insect to exhibit this phenomenon is the locust, with whom the profound effect on behaviour leads to the classification of the two phases; solitarious, where locusts actively avoid of other locusts, and gregarious, where locusts are strongly attracted to other locusts. It has been shown that food distributions at both small and large scales have an effect on the process of gregarisation. While gregarisation offers advantages, such as greater predator avoidance, the relationship between phase polyphenism and potential foraging benefits is still not fully understood.

Using a previously developed partial differential equation model of foraging (Georgiou et al. 2021), we explore the foraging advantage of gregarisation within increasingly heterogeneous environments. We begin by examining a single two dimensional simulation of a density dependent phase polyphenic organism within a spatially heterogeneous environment. We then look at the steady state foraging advantage, with a fixed portion of the population being gregarious, in environments ranging from homogeneous to very spatially heterogeneous. Finally, we perform a parameter sensitivity analysis to show that spatial heterogeneity has the greatest effect on foraging advantage. Consequently, in increasingly heterogeneous food environments it is better to be gregarious than solitarious. Conversely, the foraging advantage disappears in homogeneous environments.

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Keywords: *Locusts, PDE, collective behavior, foraging*

Should I trust that model?

Dean Holzworth [a], **Val Snow** [b] **and Neil Huth** [a]

[a] *CSIRO Agriculture and Food, Toowoomba 4350, Australia,* [b] *AgResearch, Lincoln 7674, New Zealand,*
Email: dean.holzworth@csiro.au

Abstract: The answer is no! You shouldn't trust the model; its outputs should be treated as suspect until proven otherwise. This stands even for models that you have used before and have some confidence in. This is something that experienced modellers know well and something that early career modellers need to learn. Perhaps a better question is "Is that model fit for my purpose?". Traditionally, confidence is gained by looking at comparisons of model outputs and measured data, but this is only part of the story. As the problems which models are applied to become more complex, there is increasingly less data, and less reliable data with which to test model outputs so statistical methods alone are not sufficient. There are many factors that define whether the model is going to be useful to you. Building on Snow (2016), below are some things to look for when building trust in a model.

How has the model been tested? What degree of comparison has been made with measured data? If there are data available, or should be available, for testing but no such comparisons have been made, then perhaps your relationship with the model should end immediately. If data is used for testing, does the temporal and spatial extent of the measured data coincide with your particular purpose for the model? To determine this, the tests will need to carefully describe the measured data, the experimental treatments, locations etc. When looking at how well the model fits the measured data, remember that there is always a great deal of uncertainty around the data as well as the model outputs. The model fit won't be perfect but is it good enough for your purposes? There will always be gaps in the measured data and it might not cover the regions or scenarios that you plan on using the model for. Some model developers provide sensibility tests to cover these gaps – and we would argue that more of this should be done. These are comparisons against 'expert opinion'. They might be a series of scenario runs for different locations or different model configurations with some text that says why the comparison makes sense.

How has the model been developed? How robust is the software development process used by the developers of the model? The scale of the development determines the degree to which a formalised software development process has been used. If the model has been built by a single developer, then the process will be simpler. For development teams, a more formal approach is needed. In all cases though, you should look for the use of version control, the presence of automated testing (changing the source code or test data triggers a build and test), the presence of good documentation, the presence of a test suite. Peer review of all changes to source code or testing data, needs to be a core part of the development process and this is one of the problems with sole developer efforts. Peer-review also helps find defects and weaknesses in the model. The scientific community peer-reviews work through conference articles and journal papers. The same level of peer-review needs to happen in the software development community.

Is the model understandable and defendable? Models that are presented as black boxes make it very difficult (almost impossible) to comprehend how they work. Transparency is needed to be able to see inside the box. If the model is open source, or the source is made available by other means, then everything is visible but often the complexity (e.g., number of files, classes, functions) gets in the way of transparency. Good, up-to-date documentation can help overcome this and make it clearer whether the level of abstraction is appropriate and what assumptions the model developer has made. Perhaps model explorers have a role here as well. These are sensibility tests (live or pre-run) that are available for others to explore model behaviour.

Have you used the model in the past? Trust comes with positive past experiences of the model. If you haven't used the model, look at the experiences of others in the scientific literature or in the model's user community.

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Keywords: *Model, trust, confidence, model evaluation*

Operationalizing resilience as pathway diversity in a mosaic landscape

Steven J. Lade[a,b], My Sellberg[b], Jan Kuiper[b] and Erik Andersson[b]

[a] *Fenner School of Environment and Society, Australian National University, Canberra, Australia*
[b] *Stockholm Resilience Centre, Stockholm University, Stockholm, Sweden*
Email: steven.lade@anu.edu.au

Abstract: Resilience is an increasingly popular concept that is understood and operationalized in a wide variety of ways. Approaches to understanding resilience from psychology and sociology emphasize individuals' agency but obscure systemic factors. Approaches to understanding resilience stemming from ecology emphasize system dynamics such as feedbacks but obscure individuals. Approaches from both psychology and ecology examine the actions or attractors available in the present, but neglect how actions taken now can affect the configuration of the social-ecological system in the future.

Here, we test an approach called "pathway diversity" that links existing individual, systems, and temporal theories of resilience into a common framework. A pathway diversity approach requires modelling the diversity of options available to actors (or set of actors), and how those available options change over time. Resilience is greater if more actions are currently available and can be maintained or enhanced into the future. Previously, the diversity of pathways was computed using a stochastic Monte Carlo approach; here, we derive a deterministic algorithm using matrix algebra to compute pathway diversity more efficiently.

We test the pathway diversity approach in a mosaic landscape in the Västra Harg region of Sweden. Mosaic landscapes have long been recognized for hosting a wide range of values for people and biodiversity. Through a patchy structure of different land uses, they provide renewable resources, such as food and timber, recreational and regulating services, as well as habitats for different species. As biodiversity is continuing to decline rapidly worldwide, the multifunctional potential of these landscapes to sustainably produce food and other services, while simultaneously conserving biodiversity and providing space for recreation is urgently needed.

We develop methodological advances that allow pathway diversity to be computed more efficiently. We also modify the approach to account for the presence of both actor and landscape-scale strategies. Actor strategies that we considered included meat farming, milk farming, fodder production, food production, commercial forestry, eco-tourism and conservation forestry. Landscape-scale strategies included cross-sectoral collaboration and coordination in governance, awareness raising and education, supporting land-based entrepreneurship, building local community and climate adaptation.

Our pathway diversity analysis shows that forestry strategies, in this region, are generally more resilient than agricultural strategies, due largely to the high risk of exit from agriculture. Our results also shows that policies that enhance the viability of a specific strategy can undermine an actor's resilience overall, if the policy makes a strategy more attractive that is subject to lock-in.

Keywords: *Resilience, modelling, pathways*

New frontiers in understanding and modeling waterlogging impacts on plants

Ke Liu and **Matthew T. Harrison**

Tasmanian Institute of Agriculture, University of Tasmania, Burnie 7320, Tasmania, Australia
Email: ke.liu@utas.edu.au; matthew.harrison@utas.edu.au

Abstract: Process-based simulation models aid scientific endeavour in understanding and quantifying the impacts of biophysical factors on crop growth, development and production. While the science underpinning crop growth modeling under optimal conditions has advanced over recent decades, our knowledge of ecophysiological processes underpinning waterlogging impacts on plants has received relatively little attention. As extreme climatic events associated with the climate crisis become more frequent, crop waterlogging will become an increasingly real risk for many environments and production systems.

To identify and compare biophysical, chemical and ecophysiological crop growth process in models that are influenced by waterlogging, we reviewed conceptual approaches used in several models (e.g., APSIM, AquaCrop, CROPR, DRAINMOD, SWAP-WOFOST, GLAM-WOFOST, SWAGMAN Destiny). We show that many models simulate waterlogging stress through reduction of air-filled soil pore space, often with consequences for root growth. However, subsequent effects of excess water stress on crop growth are then modelled in a variety of ways. In some cases, superfluous soil water causes plant biological stress, restricting biomass accumulation and translocation of assimilate (e.g., AquaCrop), altering processes prior to biomass accumulation such as light interception (e.g., APSIM) or photosynthesis and carbohydrate accumulation (e.g., SWAGMAN Destiny). While many models account for waterlogging stress relative to crop stage, few models account for delays in phenology typically caused by waterlogging, although APSIM-Barley and APSIM-Soybean are exceptions to this rule. Of the point-based dynamic models examined in our review, APSIM-Soybean, APSIM-Barley and APSIM-Oryza simulations most closely matched the observed data, while GLAM-WOFOST achieved the highest performance of the spatial-regional models examined. We suggest that a comparison of models specifically designed for waterlogged conditions (e.g., APSIM-Oryza) with models developed for dryland conditions (e.g., APSIM-Wheat) using experimental information derived from waterlogged conditions would advance our understanding of both: (1) processes impacting crop growth; and (2) the extent to which existing frameworks are fit-for-purpose.

We conclude that priority areas for future research on modeling plant and systems waterlogging should account for: (1) the phenology of stress onset; (2) aerenchyma (where applicable); (3) root hydraulic conductance; (4) nutrient-use efficiency; and (5) plant ion (e.g. Fe/Mn) tolerance. Incorporating these processes into models - together with a more systematic model intercomparison using consistent initialisation data - would improve our understanding of the importance of such factors in a systems context while accounting for temporal biological feedbacks, emergent properties and sensitive variables responsible for growth limitation and grain yield losses under waterlogging.

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Keywords: *Crop models, soil waterlogging, modelling intercomparison and improvement*

Diuretic-based mitigations of leaching and nitrous oxide emissions from urine patches: scaling from patch to paddock

Val Snow [a], **Esther Meenken** [a], **Rogerio Cichota** [b], **Dean Holzworth** [c, a] **and Robyn Dynes** [a]

[a] AgResearch, Lincoln 7674, New Zealand, [b] Plant and Food Research, Lincoln 7674, New Zealand,
[c] CSIRO Food and Agriculture, Toowoomba 4350, Australia
Email: val.snow@agresearch.co.nz

Abstract: Leaching and nitrous oxide emissions from grazed pastures are driven by highly concentrated urine patches deposited onto a small fraction of the grazed area. Previous work, at the scale of a urine patch, has shown that adding diuretic components to the diet of ruminants will reduce the N load in urine patches and reduce emissions of N from the patch. However, diuretics also increase the number and size of urine patches. Conceptually (Figure 1) we know that there are both reinforcing and antagonistic forces operating so it is uncertain how effective diuretics will be at the paddock scale. Here, we sought to understand how the effectiveness of a diuretic for emissions reduction varied as the spatial scale increased from < 1 m^2 (a urine patch) to several hectares (a paddock). To do this we used a validated simulation methodology designed for heterogenous urine patches within a paddock (Snow et al., 2017) of a farm.

Patch-scale simulations showed that reducing urine patch load would decrease both leaching and nitrous oxide emissions. Paddock-scale simulations suggested that the diuretic would be effective at low stocking rates with reductions in emissions of up to 40%. The effectiveness of the diuretic decreased as stocking rate rose and was largely ineffective above 3 cows /ha. The major cause of the decline in effectiveness was the increase in area of the paddock affected by urine patches with short (< 6 months) intervals between successive dispositions – this increase was stronger at high stocking rates than lower ones.

These results show the importance of simulation technologies to scale results that can be found by measurement (i.e., a patch) to scales that are meaningful but unmeasurable (a paddock or whole farm).

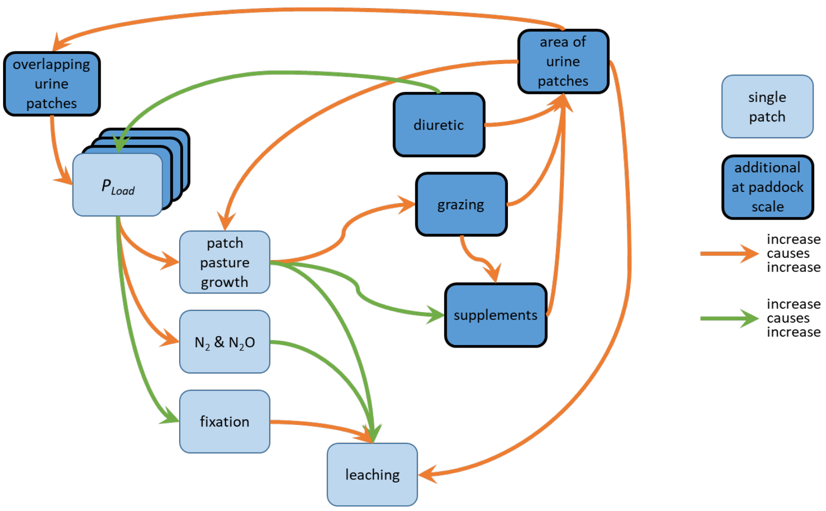

Figure 1. Conceptual influence diagram showing the effect of urine patch load (P_{Load}) on leaching at the single-patch scale (light blue) and the scale of a representative paddock within a farm (dark blue).

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Keywords: *APSIM, process-based simulation, pastoral farming, nitrogen emissions*

Simulating organ biomass variability and carbohydrate distribution in perennial fruit crops

Junqi Zhu [a]

[a] *The New Zealand Institute for Plant & Food Research Limited, Blenheim 7201, New Zealand*
Email: junqi.zhu@plantandfood.co.nz

Abstract: Variability in fruit quality greatly impedes the profitability of an orchard. Modelling can help find the causes of quality variability. However, studies suggest that the common assimilate pool model (Brown *et al.*, 2019) is inadequate in terms of describing variability in organ biomass. The aim of the current study was to compare the performances of the common assimilate pool (CP) and phloem carbohydrate transport (CT) models (Seleznyova and Hanan, 2018) in simulating phloem carbohydrate concentration ($c(x)$, x represents the position in the transport pathway) and organ biomass variability within the whole-plant functional-structural grapevine (*Vitis vinifera* L.) model that we developed before.

The CP model assumes that the ability of developing plant organs to attract carbohydrates is based on sink strength alone, while the CT model assumes that the ability of developing plant organs to attract carbohydrates is based on sink strength AND topological position of the organ AND the carbohydrate concentration gradient. The same functions that define the carbon loading and unloading processes and their repose to c_p for each organ were used for both models. The only difference between the two models was the method for solving the $c(x)$. The CP model had one universal $c(x)$ value for the whole plant, while the CT model solves the $c(x)$ value at each location of the plant.

The CT model was calibrated using a detailed potted experiment that entailed three levels of leaf area per vine during the fruit ripening period: 0, 25, and 100 leaves per vine. A statistical approach was developed for parameter optimization. The CT model was first run many times with a wide range of parameter combinations. This gave 2916 data points to generate emulators using the R package GPfit. The emulators were further used for parameter optimizations using the DEOptim package in R.

The model analysis showed that under a homogenous canopy architecture where all grape bunches were equally close to the carbohydrate sources, the CP and CT models produced very similar results. However, under a heterogeneous canopy architecture with variable distance between bunches and carbohydrate sources, the coefficient of variation for fruit biomass rose from 0.01 to 0.17 as crop load increased. These results indicate that carbohydrate allocation to fruits is affected by both the crop load and fruit distribution, which is not adequately described by the CP model.

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Keywords: *Carbohydrate transport, phloem carbohydrate concentration, within-plant variation*

Trade strategies to mitigate the global impact of regional wheat production shocks

P. Golding [a], S. Kapadia [a], S. Naylor [a], J. Schulz [a], H.R. Maier [a], U. Lall [b] and M. van der Velde [c]

[a] School of Civil, Environmental & Mining Engineering, University of Adelaide, Adelaide, South Australia, [b] Department of Earth and Environmental Engineering, Columbia University, New York, NY, USA, [c] European Commission, Joint Research Centre, 21027 Ispra, Italy
Email: holger.maier@adelaide.edu.au

Abstract: Shocks in regional wheat production can have severe repercussions for dependent importing countries elsewhere. Impacts due to climate extremes, natural disasters, but also (subsequent) export restrictions, reduce volumes of crop produce on international markets that can jeopardize local to national food security. In this manuscript, we consider the capacity of the global wheat trading network to absorb such shocks and identify the trade links between exporting and importing countries that are critical to do so.

We specifically consider two questions:

1. Without changing current trade links, can quantities traded be altered to improve the adaptive capacity of the global trade network to mitigate the impact of shocks?
2. In the event of various shocks, which trade links must be versatile to ensure optimal reduction of global wheat deficit?

We impose wheat production shocks in Eastern Europe and Russia, the USA, and Australia to simulate shocks in line with historic events. Assuming that increased prices would stimulate exporting countries to tap into their storage after satisfying domestic demand, we evaluate the most important trade links to optimally reduce the global wheat deficit. As such, we employ ant colony optimisation to reduce the global wheat deficit caused by the regional shocks. The ease with which different trade strategies can be implemented in practice is also considered. Countries cannot establish new trading links but can alter traded amounts. Thus, the minimum global deviation of estimated current traded quantitities is also minimised. The decision variables considered in the optimisation problem are the volumetric tradable quantities of wheat between countries, which allows for consideration of alternative trading strategies on a global scale. Two cases were considered, 1) all countries were able to access their initial storage, in all shock scenarios, to assist in the global reduction of deficit; 2) Russia, the largest exporter, was disallowed access to its storage for export purposes in accordance with historic requirements.

We find that the current global trade network could not completely mitigate the deficit incurred as a result of the simulated shock. However, by redistributing trade quantities on existing trade links, the deficit was reduced considerably in all scenarios. Out of 619 trade links considered, 240 were found to be directly used in achieving minimum deficit solutions. However, while there is significant benefit in increasing the number of active trade links initially, this benefit diminishes towards the lower end of global deficit values. Activating the 30 most important trade links accounted for reducing the global wheat deficit in all scenarios by 80 to 95%.

The study examines the (theoretical) ability of the trade network as a whole to mitigate the impact of shocks. Importing countries with only a few trading partners are at risk to wheat production shock occurring in those exporting countries. In addition, countries that are generally reliant on a variety of suppliers, but come to rely on a single supplier after a shock elsewhere, may find it difficult to increase their import if only low volumes were traded previously. The interplay of a production shock in one region, and a withdrawal from the global wheat market in another region in response to this, can lead to unexpected consequences. Barring access to this country's storage, can affect more countries than solely those directly trading with this country due to the overall network properties. In our analysis, influential exporting countries were those characterized by their ability to alleviate the shock incurred, which depends both on their interconnectivity with affected countries and the amount they have in storage.

Keywords: *Global food security, shocks, trade, wheat, ant colony optimisation*

A hybrid approach of water-related energy quantification of the food system

K M Nazmul Islam [a,b,e], Steven J. Kenway[b], Marguerite A. Renouf [c] and Thomas Wiedmann [d]

[a] School of Chemical Engineering, University of Queensland, QLD, 4072, Australia, [b] Australian Centre for Water and Environmental Biotechnology (formerly AWMC), University of Queensland, QLD, 4072, Australia, [c] QUT Centre for Agriculture and the Bioeconomy (CAB), Queensland University of Technology, QLD, 4000, Australia, [d] Sustainability Assessment Program (SAP), School of Civil and Environmental Engineering, UNSW, Sydney NSW 2052, Australia, [e] Institute of Forestry and Environmental Sciences, University of Chittagong, Chittagong 4331, Bangladesh

Email: kmnazmul.islam@uq.net.au

Abstract: The food system is an interconnected system of agriculture and food production activities. Water and energy management for the food system is now facing tremendous challenges to comply with the Sustainable Development Goals (SDGs), such as Sustainable Cities and Communities (SDG11), Responsible Consumption and Production (SDG12), and climate action (SDG13). The challenges are more aggravating due to the interdependence of food, water, and energy within the food system. The interdependence is often observed in the form of (a) energy input for food and water production, as well as, wastewater treatment of food processing; (b) water inputs for food and energy production, and (c) greenhouse gas (GHG) emissions from the water-related energy (energy use related to water and steam application and treatment), and other energy (e.g. transportation, machine running) use.

Kenway et al. (2019) demonstrate up to 12.6% of total national primary energy use can be influenced by water use mostly focusing on the water and wastewater utilities. Our previous study shows, there is a lack of water-related energy assessment of the food system as part of the Food-Water-Energy-Greenhouse gas emission (FWEG) nexus focusing on GHG emission, cost implications, and structural paths (Islam et al. 2021). These aspects need to be assessed for a better understanding of energy and GHG emission, and associated cost reduction through water management of the food system. Given this context, our work presents a robust analysis of energy, GHG, and cost implications of water use in the food system for the first time considering Australia, as a case study.

The system boundary of this study is the Australian national economy in 2015, and the Environmental Input-Output model, and Structural Path Analysis applied to analyze the nexus. The results show that the food system uses 49% (7,633 GL) of total water input to the national economy. That amount of water use accounts for 189 PJ water-related energy use, which is around 55% of total energy use in the food system (346 PJ). The highest water-related energy use was from natural gas (~70 PJ), followed by fossil fuel-based oil products (~45 PJ). The GHG emission (13.5 Mt CO_{2eq}) of water-related energy is around 3% of national emissions; and 5% of the energy-related emissions of the economic sector. The estimated monetary value of the water-related energy use in the food system was around AUD 2.5 billion, of which 57% contributed by the fossil-fuel based oil and petroleum products, 24% by natural gas, 16% by electricity, and remaining by coal and biomass (e.g. bagasse and wood chips). Water-related energy use in the identified critical food sub-sectors varies from 40% to 66%.

Our findings suggest that water management is a key for energy and associated GHG impacts reduction in the identified sub-sectors of the food system. The approach used can be also applicable to other countries depending on the national circumstances, and data availability.

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Keywords: *Sustainable development goals, climate-friendly food system, climate change mitigation, food-water-energy nexus*

Economically optimum N fertiliser decisions for rice cultivation in Sri Lanka: Does soil type matter?

H. Kanthilanka [a], R.J. Farquharson[a], T. Ramilan [a,b] and J. Weerahewa [a,c]

[a] *School of Food and Agriculture, The University of Melbourne, Australia,* [b]*Massey University, New Zealand,* [c]*University of Peradeniya, Sri Lanka.*
Email: hjayasekara@student.unimelb.edu.au

Abstract: In rice (*Oryza Sativa*) production, appropriate nitrogen (N) management needs to consider the relationship between the rate of N fertiliser application, time of application and crop yield for different soil types. N demand is a crop-specific factor, while N supply is related to soil characteristics and crop management practices such as N fertilisation. Balancing N supply against demand makes N use more efficient by avoiding N losses from the system, which impacts farming profit and the environment. A coupled, biological and economic modelling approach was adopted to identify the economic optimum rate of N (EORN) for rice cultivation in three soil types in Sri Lanka (Figure 1). The three soil types are Low Humic Gley (LHG) poorly drained soil, Reddish Brown Earth (RBE) well imperfectly and well-drained soil.

The APSIM-Oryza model was parameterised for the conditions of the study area. Model validation confirmed that there was good agreement between actual and simulated rice yield. The validated APSIM-Oryza model was used to evaluate the rates of N application between 0 and 300 kg N/ha/season for the last 20 years of weather. Rice yield response to N varied between soils, and yield variability over the years was also observed due to weather. The highest potential yield at the median and lowest yield variability across years was observed in LHG poorly drained soil which is highly suitable for rice cultivation. RBE well-drained soil showed poor response for applied N with lowest yield potential while RBE imperfectly drained soil varied between responses of other soil types.

The simulated rice yields for each N application was considered as the inputs to an economic evaluation of the N decisions. A modified Mitscherlich-Baule yield response function was used to fit the relationship between N rate and grain yield for each soil type since the visual pattern of APSIM-Oryza simulated yield best matched with the functional form. Profit maximising conditions applied to the yield responses developed EORN of 228, 156, and 118 kg N/ha in LHG poorly drained soil, RBE imperfectly drained soil and RBE well-drained soil, respectively. Rice yields at the economic optimum were 6.1, 4.0 and 2.8 t/ha, respectively. The economic optimum was highly price-sensitive; hence the quantitative values could be varied with changing rice selling price and N fertiliser price. However, the results indicated that investment in N fertiliser needs to consider the type of soil due to differences of yield responses in soil types; hence blanket application of N fertiliser over soil types caused to deviate from a maximum profit of rice cultivation in given soil types.

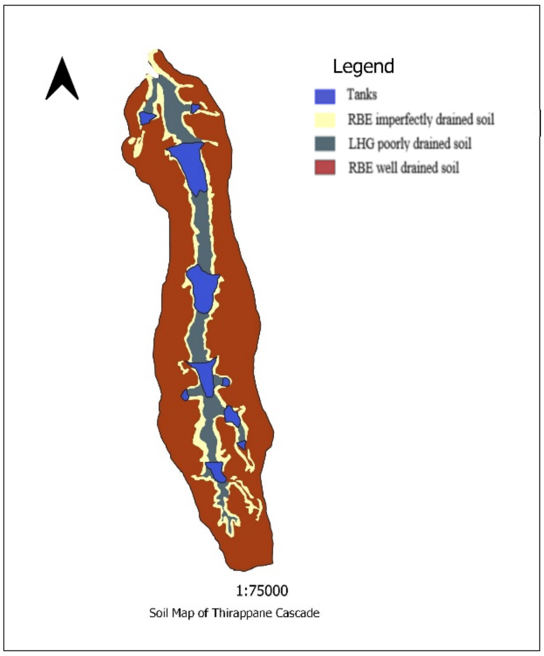

Figure 1. Soil map of study location

Keywords: *APSIM-Oryza, economic optimum, nitrogen fertiliser*

Impacts of localizing food system on farmers' livelihood resilience

P.S. Loo, F. Önal, K. Bax, M. Smairy and V. Surovets

Department of Geography, System Dynamics, University of Bergen, Norway
Email: pei.loo@student.uib.no

Abstract: The concept of localizing food system gained traction in academic, policy, and development sectors in recent years, especially building resilience. The local council has a growing role in designing an efficient and equitable food system for community wellbeing. However, it is crucial to adopt fundamental solutions instead of short-term solutions of the problem. Also, an analysis should be conducted to understand both the positive and the unintended consequences of the proposed policies. To address this knowledge gap, the model is developed to explore policies' impact on building farmers' livelihood resilience in facing climate disturbance. The proposed combination of farmer market capacity expansion, farmer market organization marketing, setting up food and food box delivery policies deliver the best outcome in building resilience. The key messages of the project are, first, encourage a diversity of responses in building resilience; second, finding balance in managing limited resources for coping capacity versus future adaptative capacity; third, using group model building to build ownership of various stakeholders on the policy implementation. The potential next steps include quantifying resilience and diversifying types of consumers.

Keywords: *Farmers' livelihood resilience, localizing food system, system dynamics*

Using milk tanker pickup and weather station data to quantify the impacts of heat stress on milk production in Australia

R.S. Meyer [a], A-M Graham [a], Hepworth, G. [b] and R.J. Eckard

[a] *Faculty of Veterinary and Agricultural Sciences, University of Melbourne Parkville Victoria*
[b] *Statistical Consulting Centre, University of Melbourne Parkville Victoria*
Email: meyer.r@unimelb.edu.au

Abstract: Due to high metabolic heat production, dairy cows are more sensitive to heat stress than other livestock. This has consequences on the animal's welfare and productivity. Reductions in milk production can occur from relatively mild temperatures with the degree of impact increasing with increasing severity of heat exposure. The degree to which heat stress impacts milk production, farm income, and milk supply is becoming increasingly important as the duration and frequency of heat waves increases. This analysis aims to provide estimates of the sensitivity of milk production on Australian dairy farms under heat stress situations.

The milk tanker pickup data from three dairy companies was used to investigate the on-farm impacts of heat stress on milk production in three regions of Australia. Milk production and weather data were matched based on the postcode of the farm and Bureau of Meteorology weather station. Weather data were used to calculate the temperature-humidity index (THI) using a formula typically used in Australian studies. The THI is commonly used to quantify the effects of heat stress by combining the effects of temperature and relative humidity. Data that did not meet pre-defined quality criteria were eliminated from the analysis. For instance, records that occurred three or more days since the previous milk pickup, data from farms with less than one year of observations, and years in which more than 10 records were missing between October and April, inclusive, were excluded. Over 960,000 records from 1,286 farms are included in the regional analysis. Linear mixed effect models were fitted to the data from each of three regions using R.

The estimated response of milk volume (L) and milk solids (kg) and associated 95% confidence intervals (CIs) are summarised in Table 1. Models using THI values averaged over 7-days, consistently performed better than those averaged over shorter periods. THI values based on minimum and average temperatures performed slightly, but consistently, better than those based on maximum temperature.

Table 1. Change in milk production with increasing THI in three regions of Australia

	Gippsland	Murray	SE QLD - NE NSW
Volume (L/THI unit) (95% CI) Best performing THI metric	-13.7 (-14.5, -12.8) Min THI avg 7 d	-10.3 (-11.3, -9.2) Min THI avg 7 d	-10.8 (-16.7, -4.9) Min THI avg 7 d
Milk Solids (kg/THI unit) (95% CI) Best performing THI metric	-1.38 (-1.45, -1.32) Avg THI avg 7 d	-1.25 (-1.32, -1.17) Avg THI avg 7 d	-0.66 (-1.07, -0.25) Min THI avg 7 d

The improved performance of average and minimum THI compared to maximum THI supports the hypothesis that cool night-time temperatures are important in mitigating the impacts of high daytime temperatures. THI metrics calculated over seven days, which performed better than those calculated over shorter periods, supports previous findings of lag effects and the impacts of prolonged heat. The larger impact of heat stress on milk production in Gippsland may reflect dairy cows being comparatively sensitive to heat in this relatively cool region, a lack of management interventions, or a combination of both. This analysis addresses the current losses associated with heat stress. This, accompanied by work on the cost effectiveness of available mitigation options, will assist in effective adaptation to the impacts of heat stress on dairies.

Keywords: *Milk, heat stress, cows, production, temperature-humidity index*

Resilience of agri-food supply chains: Australian developments after a decade of supply and demand shocks

Firouzeh Taghikhah [a], Derek Baker [b], Moe Thander Wynn [c], Michael Billy Sung [d], Stuart Mounter [b], Michael Rosemann [e], and Alexey Voinov [f]

[a] College of Asia and the Pacific, Australian National University, Australia.
b UNE Centre for Agribusiness, University of New England, Australia.
c Faculty of Science and Engineering, Queensland University of Technology, Australia.
d Consumer Research Lab, Curtin University, Australia.
e Faculty of Business & Law, School of Management, Queensland University of Technology, Australia.
f Centre on Persuasive Systems for Wise Adaptive Living, University of Technology Sydney, Australia.
Email: Firouzeh.th@gmail.com

Abstract: Australian agribusiness has made a significant transition from commodity delivery to consumer-oriented value addition. Its agri-food sector is mainly export-oriented and operates at a large scale, though its considerable distances, linking production, markets, inputs, and infrastructure, make it a high-cost operator relative to international competitors. A succession of shocks to both demand and supply over the last decade has challenged the Australian agri-food supply chains in the forms of natural disasters, geopolitical maneuvering in trade policies, a pandemic, and drought. These shocks are in many cases associated with broader trends such as climate change, expanded biosecurity threats, more fickle consumer needs, and changes in labor mobility. The current concentrated retail environment creates an increasing demand to design resilient supply chains. It looks for unique ways to accommodate the Australian commercial and physical environment and farm management systems. Nonetheless, supply chain management has adhered to conventional performance metrics associated with cost and capacity utilization. In response to the sequence of shocks, digital technology has rapidly matured and provided a plethora of entirely new design options. The related research and practical applications of these technologies are dominated by improved productivity, targeting quality and quantity to the market, and logistical efficiency. These estimates refer to conditions not disturbed by the shocks outlined above, and they are heavily reliant on efficient supply chains to deliver them. That is to say, resilience in supply chains is mostly related to efficiency imperfectly and represents a trade-off between costs and redundancy, for example. Hence, this chapter focuses on aligning the definitions of agri-food supply chain resilience with management needs and highlights the potential applications of technologies and information systems in advancing resiliency. It outlines a set of shocks or challenges associated with different commodity sectors and identifies thematic benefits of resilience at varying echelons of supply chains. Several sources, including interviews with industry specialists and literature review, are used to extract potential digital solutions and discuss their impact on the resilience indicators. Results are compiled across settings and weightings, representing supply chain performance and resilience priorities to provide research-informed, practically applicable digital interventions.

Keywords: *Resilient, food security, artificial intelligence, sustainable development*

A nationally scalable approach to simulating soil organic carbon in agricultural landscapes

K.M. Coelli[a,e] **, S.B. Karunaratne**[b] **, J.A. Baldock**[c]**, S. Ugbaje**[b,d]**, A.J.V. Buzacott**[a]**, P. Filippi**[a]**, S. Cattle**[a] **and T.F.A. Bishop**[a,d]

[a] School of Life and Environmental Sciences, The University of Sydney, Sydney, New South Wales, [b] CSIRO Agriculture and Food, Black Mountain, Australian Capital Territory, [c] CSIRO Agriculture and Food, Adelaide, South Australia, [d] Sydney Informatics Hub, The University of Sydney, Sydney, New South Wales, [e]CSIRO Data61, Brisbane, Queensland
Email: kate.coelli@sydney.edu.au

Abstract: The world's soil provides a large potential sink to sequester carbon, but in order to incentivise increases in soil organic carbon (SOC) and for countries to use increases in SOC to meet their international greenhouse gas emission commitments, we need to accurately estimate changes in SOC. Statistical and process-based models are often used to estimate these changes, and Australia's greenhouse gas reporting framework uses Full Carbon Accounting Model (FullCAM). The dynamics of soil carbon within the FullCAM modelling framework is quantified using the Rothamstead Carbon Model (RothC). The model's ability to estimate change of SOC with time depends on (a) accurate estimation of the key drivers of model inputs and (b) the fate of those drivers on dynamics of SOC through model parameter calibration. For instance, SOC estimates could be improved with more accurate estimation of the plant residues entering the soil. Currently, the reporting framework uses crop type information based on broad spatial supports such as Statistical Area 2 (SA2) regions to derive plant residue inputs for RothC. This is a much coarser spatial resolution than the true spatial variability of plant residues.

In this work we present an application of RothC with plant residue inputs derived from freely available remotely sensed evapotranspiration (ET) data, NDVI and a land use specific scaling parameter. This is demonstrated using two case studies: Muttama Creek - a 1025 km^2 catchment and Hillston: a 2650 km^2 district, both in New South Wales (NSW). The Muttama Creek catchment is predominately dryland cropping and grazing land uses, while Hillston is a semi-arid irrigated cotton-growing district.

The model is initialised using SOC fractions, predicted from the spectral library built under an Australian-wide soil sampling project (SCaRP - Baldock et al., 2013a) and has an improved water balance model which uses remotely sensed ET (Wimalathunge and Bishop, 2019) to represent plant water use. This is an improvement on the water balance model built into RothC which uses evaporation to estimate plant water use.

Each catchment consists of two temporal surveys. While Hillston demonstrates a longer timeframe (2002-2015) to observe changes in SOC between surveys, the timeframe of the Muttama Creek (2013-2019) study is similar to the time between repeat sampling rounds of a soil carbon project, under the Emissions Reduction Fund (ERF - the Australian Government's carbon crediting program). In soil carbon projects under the ERF, change in SOC from the project must be reported to the Government at least every five years, for 25 years (according to a strict set of reporting guidelines). To receive carbon credits after their first report, there must be an observable change in SOC between sampling rounds.

This study shows potential to scale ET and NDVI information according to land use to estimate plant biomass carbon inputs (C inputs) to use as an input to the RothC model. Across the two catchments used to demonstrate this approach, 77 sites, sampled at two time points were used to calibrate the model according to the four land use classes tested in this study. When the simulated SOC results were compared to the observed values for the second sampling time, the cropping systems (Lin's concordance correlation coefficient (LCCC) = 0.61) performed the best, followed by native grazing systems (LCCC = 0.46), modified pasture systems (LCCC = 0.33) and irrigated cropping systems (LCCC = 0.11).

Keywords: *Next generation soil carbon models, process-based model, RothC, soil carbon model, integration of data streams*

Integrating advanced knowledge of soil organic carbon stabilisation into carbon modelling

Yunying Fang [a], Susan Orgill [a], Cathleen Waters [a], Annette Cowie [a], Bin Wang [a], Ehsan Tavakkoli [a] and Lukas Van Zwieten [a]

[a] *NSW Department of Primary Industries, NSW, Australia.*
Emails: yunying.fang@dpi.nsw.gov.au; susan.orgill@dpi.nsw.gov.au; cathy.waters@dpi.nsw.gov.au; annette.cowie@dpi.nsw.gov.au; bin.a.wang@dpi.nsw.gov.au; ehsan.tavakkoli@dpi.nsw.gov.au; lukas.van.zwieten@dpi.nsw.gov.au

Abstract: Soil organic carbon (SOC) stocks in agroecosystems have considerably declined largely due to cultivation and overgrazing, resulting in land degradation and the potential to exacerbate global warming. This prompts necessities in widespread implementation of practices that improve soil condition, and policies and markets that enable to increase carbon sequestration. Integrating advanced knowledge of SOC dynamics into carbon models is required to better assess the potential of SOC sequestration under different land use management and environmental conditions.

Soil organic carbon stabilisation processes, recognized as key to understanding carbon flows and stocks, is a subject of much research (Lehmann et al., 2020). Soil organic matter contains varied molecular diversity and composition, resulting in different vulnerabilities to climatic and environmental conditions, and adding further complexity in SOC dynamics at various spatial and temporal scales. Decomposition and stabilisation of SOC are the result of complex interactions among biotic, edaphic, and climatic factors. Moreover, physical fractionation of SOC and molecular techniques improve mechanistic understanding of soil carbon deposition, decomposition, transformation, and stabilization processes. Recent evidence shows that SOC residing in different locations within the soil matrix has fundamentally different formation pathways and persistence. Organic carbon associated with minerals and occluded in micro-aggregates are more stable and persistent, compared to OC in macro-aggregates and particulate form. Soil management that influences microbial processes may result in increased carbon flow to stable SOC by accelerating the breakdown of plant residues and particular organic matter. Microbial residues are a significant source of stable SOC as a result of being preferentially protected through mineral associations.

However, such newly acquired knowledge in the dynamic nature of SOC behaviour and persistence has not been reflected in global carbon models. Current modelling efforts to quantify SOC dynamics in response to changes in management and global environment do not accurately represent the size, distribution, and flux of carbon within, and from soil. Soil organic carbon stabilisation has not yet been explicitly integrated into numerical soil biogeochemistry models. There are a few attempts to modify the prevalent biogeochemical models such as CENTURY by parameterizing conceptual SOC pools with measurable SOC fraction data to determine the turnover rates of SOC pools. New models need to consider integrating advanced knowledge in mechanic understanding of SOC stabilisation in combination with new and growing soil datasets that capture decomposition responses caused by changes in land management and climate.

Managing SOC in agroecosystems to restore degraded lands and slow global warming requires advanced knowledge of SOC dynamics and stabilisation. Physically separated SOC fractions provides promise as a new conceptual framework to build SOC dynamics into biogeochemical models. Such an integrated model is likely to provide more reliable estimates of carbon sequestration and will help to identify and prioritise recommendations to policy makers and management practitioners.

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Keywords: *Soil organic matter, soil management, decomposition, persistence, climate change*

Soil organic carbon sustaining maize yields in China

Puyu Feng [a], Bin Wang [b], Matthew Tom Harrison [c], Jing Wang [d], Ke Liu [c,e], Mingxia Huang [d] and Kelin Hu [a]

[a] *College of Land Science and Technology, China Agricultural University, Beijing 100193, China*
[b] *NSW Department of Primary Industries, Wagga Wagga, NSW 2650, Australia*
[c] *Tasmanian Institute of Agriculture, University of Tasmania, Burnie 7250, Tasmania, Australia*
[d] *College of Resources and Environmental Sciences, China Agricultural University, Beijing 100193, China*
[e] *Engineering Research Center of Ecology and Agricultural Use of Wetland/School of Agriculture, Yangtze University, Jingzhou 434025, Hubei, China*
Email: fengpuyu@cau.edu.cn

Abstract: With a rapidly increasing global population and increasing uncertainty over food security, farmers are facing a dilemma of producing crops with a higher yield on the same (or even less) cultivated areas. More specifically, the mean growth rate of global crop yield must exceed 2.4% per year to feed 10 billion people by 2050s. However, the ongoing climate crisis is preventing farmers from fulfilling this goal. As current farming systems are normally designed to fit into historical climate conditions, climate change-induced changes of meteorological factors are expected to pose significant risks for future farming outputs.
Temperature is commonly reported as a key factor affecting maize yield and any changes beyond the optimal zone are likely to cause detrimental impacts on maize yields. However, less is known about how soil can modulate the region-specific impacts and whether certain soil properties can buffer the adverse impacts of climate warming. In this study, we used the Agricultural Production Systems sIMulator (APSIM) model, to investigate the impacts of multiple soil biological and physical (e.g. soil carbon and soil plant available water) properties on the responses of maize yield to growing season temperature ($S_{Y,T}$) between 1961 and 2016 in the China's maize belt. Our objectives were to address the following questions: I) how does maize yield respond to climate warming in different zones of the China's maize belt? II) how do various soil physical, hydraulic, and chemical properties modulate the impacts of climate warming on maize yield? By answering these we provide insights into the development of adaptive strategies for global warming from the perspective of soil interventions.

Results indicated a greatly varied $S_{Y,T}$ across regions with a large yield decline of 11.2% for each 1 °C warming in the mid-eastern region of the belt but a small increase of 1.5% in the north-eastern region. We found that the variations of soil inherent properties was able to explain around 77% of the spatial variations of $S_{Y,T}$. Among the included properties, soil organic carbon content (SOC) contributed most, showing positive impacts on maize yield. We also found that the regions with low $S_{Y,T}$ were those areas with high SOC content. Our findings highlight the importance of SOC in the mitigation of adverse global warming impacts. SOC is an important indicator of soil quality and soils with higher SOC tend to show better water and nutrient retention, which can then help crops buffer the impacts of increased temperature and even exploit positive effects. To ensure food security for a rapidly increasing population under a changing climate, appropriate farming management practices that improve soil quality (especially SOC) can provide farmers with a natural insurance against climate warming through a gain in yield stability and more resilient production in China's mazie belt.

***Keywords**: Climate change, temperature sensitivity, soil inherent properties, maize*

Soil carbon sequestration potential with enhanced vegetation cover: digital soil maps for NSW

Jonathan M. Gray[a], Bin Wang[b], Cathleen M. Waters[c], Susan E. Orgill[b], Annette L. Cowie[d] and Ee Ling Ng[a]

[a] *NSW Department of Planning, Industry and Environment, PO Box 644, Parramatta, NSW 2124, Australia,*
[b] *NSW Department of Primary Industries, Wagga Wagga Agricultural Institute, NSW 2650, Australia*
[c] *NSW Department of Primary Industries, 34 Hampden Street, Dubbo NSW 2830, Australia*
[d] *NSW Department of Primary Industries, Trevenna Rd, Armidale, NSW 2351, Australia*
Email: jonathan.gray@environment.nsw.gov.au

Abstract: Enhancing soil organic carbon (SOC) is recognised as a potentially important avenue for reducing greenhouse gas levels and mitigating global climate change. Carbon trading schemes such as the Emission Reduction Fund (ERF) in Australia offer incentives for soil carbon sequestration programs, but to date there has been little participation by Australian landholders in such schemes.

Potential sequestration rates following improved land management practices have been demonstrated throughout Australia and worldwide. Broad scale sequestration potential maps have been released, such as the potential capability index of Baldock *et al.* (2009) and those of the Australian Government. However, few studies have attempted to present SOC sequestration potential at a finer spatial resolution, which is needed to inform landholders on decisions on participation in carbon markets. This study (Gray *et al.* in review) demonstrates the preparation of fine scale maps with 100 m resolution that identify the local potential for SOC sequestration under a readily achievable land mangement practice, being a 10% relative increase in vegetation cover.

The study applied a digital soil mapping (DSM) method in a "space-for-time substitution" framework over NSW. Data comprised 2150 points with SOC stocks to 30 cm, which was split into 80% training data and 20% test data. A multiple linear regression model was run with 100 bootstraps to map current SOC stocks under current land use and vegetation cover, then the model was re-run with a 10% relative increase in vegetation cover. The difference between the two maps gave the sequestration potential. Random forest models were trialled but presented severe anomalies.

The potential sequestration varied from 0 to > 20 Mg ha^{-1}, with a mean state-wide potential increase of 5.4 Mg ha^{-1} over the 0-30 cm depth interval. Assuming a 20-year period of re-equilibration, this equates to an average SOC increase of 0.27 Mg ha^{-1} yr^{-1}. The sequestration potential was systematically controlled by a combination of climate, soil parent material and current vegetation cover, e.g., 1.6 Mg ha^{-1} SOC under dry climatic conditions in sandy infertile soil material with initial sparse vegetation cover, compared with 15.9 Mg ha^{-1} under wet conditions in clayey fertile soil material with moderate-high initial vegetation cover. Considering potential increase over all land uses across the state, and assuming a 20-year period for the sequestration, then some 75 Tg yr^{-1} CO_2e or approximately 58% of reported total annual NSW emissions are potentially abated.

Our estimates broadly accord with sequestration rates of 0.2–0.5 Mg ha^{-1} yr^{-1} following improved land management reported from international and Australian studies. The maps and associated products derived can serve as a useful guide in the selection of priority areas for carbon sequestration programs. They allow land holders to assess the broad potential of their properties to sequester SOC and thus inform decisions on whether to participate in carbon trading schemes. Application of our method at finer scale with higher accuracy, in combination with an efficient auditing sampling design, could form the basis of statistically reliable estimates of SOC gain, as required for participation in carbon trading schemes in Australia and beyond.

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Keywords: *Soil carbon sequestration, digital soil mapping, climate change, vegetation cover*

Eco-geomorphic feedbacks and dynamics of soil carbon in coastal wetlands

Steven G. Sandi [a], **Jose F. Rodriguez**[a], **Patricia M. Saco**[a], **Angelo Breda**[a] **and Neil Saintilan**[b]

[a] Centre for Water Security and Environmental Sustainability and School of Engineering, The University of Newcastle, Callaghan, Australia, [b] Department of Environmental Sciences, Macquarie University, Sydney, Australia.

Email: steven.sandirojas@newcastle.edu.au

Abstract: Vegetation in coastal wetlands has a high efficiency to accumulate carbon in the soils. In fact, saltmarsh and mangroves have some of the largest carbon soil stocks per area around the world. The complex eco-geomorphic interactions between flow, sedimentation and vegetation drive accretion processes which over time lead to carbon being accumulated in the soil and in the form of biomass. Under equilibrium conditions, rates of change in sea-level change are compensated by accretion, guaranteeing the survival of the vegetation over time. In recent years, however, vulnerability of coastal wetlands to accelerated sea-level rise has been recognised and it is estimated that 80% of coastal wetlands could be lost by the end of the century. Landward migration or accommodation can potentially alleviate some of these effects, but this is not always possible due to topographic limitations and physical human made barriers that impede wetland transgressions. Because of this, the survival of coastal wetland vegetation and the capacity of these systems to continue accumulating soil carbon is still highly uncertain.

Estimates of coastal wetland submergence under sea-level rise rely on modelling techniques that can represent the complex eco-geomorphic processes over time in a non-linear manner and with a good spatial resolution. Many modelling techniques use simplified methods for representing hydrodynamics drivers, which can lead to significant underestimation of coastal wetland vulnerability (Rodriguez et al., 2017). The implementation of eco-geomorphic modelling techniques are useful for exploring diverse wetland management scenarios in order to explore the fate of coastal wetlands.

We implement a model for saltmarsh and mangroves of south-eastern Australia (Rodriguez et al., 2017) and we use it to explore the dynamics of the vegetation under sea-level rise (Sandi et al, 2018 and Breda et al, 2018). . We incorporate soil carbon quantification into our eco-geomorphic model (Sandi et al, 2021) and we use it to explote explore the use of different hydraulic control measurements as a management practice and the potential outcomes of hydraulic control in terms of vegetation extent and soil carbon accumulation under sea-level rise.

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Keywords: *Saltmarsh, mangroves, soil carbon, sea-level rise*

EXTENDED ABSTRACT ONLY

Modelling and mapping soil organic carbon stocks under future climate change in New South Wales

Bin Wang [a], **Jonathan M. Gray** [b], **Cathy M. Waters** [c], **Muhuddin Rajin Anwar** [a,d], **Susan E. Orgill** [a], **Annette L. Cowie** [e], **Puyu Feng** [f] **and De Li Liu** [a,g]

[a] *NSW Department of Primary Industries, Wagga Wagga, NSW 2650, Australia*
[b] *NSW Department of Planning, Industry and Environment, PO Box 644, Parramatta, NSW 2124, Australia*
[c] *NSW Department of Primary Industries, Dubbo, NSW 2830, Australia*
[d] *Graham Centre for Agricultural Innovation (an alliance between NSW Department of Primary Industries and Charles Sturt University), Pine Gully Road, Wagga Wagga, NSW 2650, Australia*
[e] *NSW Department of Primary Industries, Armidale, NSW 2351, Australia*
[f] *College of Land Science and Technology, China Agricultural University, Beijing 100193, China*
[g] *Climate Change Research Centre, University of New South Wales, Sydney, NSW 2052, Australia*
Email: bin.a.wang@dpi.nsw.gov.au

Abstract: The management of soil organic carbon (SOC) can play a key role in its sequestration and avoiding emissions. Climate change including increased temperature and changed rainfall will influence the global SOC cycle. There are still significant gaps in our knowledge of the size of the global SOC pool and how future climate will affect SOC stocks and flows in many parts of the world. To address this gap, we used a novel method to estimate the current SOC stocks and assess the impacts of future climate change on SOC stocks as a case study in south-eastern Australia.

We used multiple sources of legacy SOC data with a range of environmental covariates to quantify the spatiotemporal dynamics of SOC stock using Digital Soil Mapping (DSM) techniques in New South Wales (NSW) (Wang et al., 2022). We aimed to provide robust projected results, using 25 available global climate models (GCMs) from the Coupled Model Inter-comparison Project Phase 6 (CMIP6) under two Shared Socio-economic Pathways (SSPs) scenarios to cover a large range in changes for two key variables that drive climate, temperature and rainfall. Our objectives were to (1) develop different DSM methods to estimate and map current SOC stocks in NSW, (2) predict the change in SOC stocks under future climate, and (3) investigate the relationship between SOC stock change and climate change. The assessment of the impacts of future climate change on total SOC stocks across NSW and understanding its environmental controls are important to predict the region's response to future climate change and develop climate mitigation strategies to meet the net zero emission target for NSW.

We found that: (1) estimated current SOC stocks in NSW decreased from east to west, (2) the most important predictors of SOC stocks in NSW were rainfall and minimum temperature, (3) multi-GCM ensemble means suggested SOC stocks would decrease by 7.6-12.9% under SSP2-4.5 and decrease by 9.1-20.9% under SSP5-8.5 across NSW under future climate, and (4) the extent of change in SOC stocks varied spatially with the largest mean decrease of SOC stocks occurring in the North Coast and South East (alpine) regions of NSW.

Projections of SOC stocks for the different Local Land Service regions obtained in our research can be used as a basis for identifying areas susceptible to SOC decline under future climates across NSW. Combining DSM with spatial databases enabled an assessment of changes in regional SOC stocks to inform land management and climate change strategies and policies. The significant decline in SOC stocks projected even under moderate climate change highlights the potential risks to landholders from engaging in carbon trading, and the expected challenges for jurisdictions with reliance on soil carbon sequestration to meet net zero greenhouse gas emission targets. Moreover, our methodology is easily transferrable to other regions where information on edaphic and landscape properties, land use, and climate data are available.

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Keywords: *Soil organic carbon, global climate models, climate change, digital soil mapping, New South Wales*

Whole-soil profile carbon dynamics in response to climate change modulated by vertical carbon transport and the priming effect

Mingming Wang[a] and Zhongkui Luo[a]

[a]*College of Environmental and Resource Sciences, Zhejiang University, Hangzhou, Zhejiang 310058, China*
Email: wmmming@zju.edu.cn, luozk@zju.edu.cn

Abstract: Vertical carbon transport along the soil profile redistributes soil carbon fractions in soil layers, which may have significant consequences on whole-soil profile organic carbon (SOC) dynamics. We developed three varieties of vertically resolved SOC models to simulate SOC dynamics (down to 2 m). The three models considered mechanisms underpinning the increased persistence of SOC in deeper soil layer depths by explicitly simulating microbial processes and the interactions between old and new carbon pools.

Model sensitivity analyses indicated that vertical carbon transport must to be considered, otherwise the profile distribution of SOC stock cannot be captured by the models. The models were further constrained by global data sets of whole-soil profile observations of vertical distribution of SOC stocks and carbon inputs, and then were used to predict the spatial pattern of the depth-specific amount of vertically transported organic carbon (*V*, g C m^{-2} yr^{-1}) and the priming effect (*PE*) intensity across the globe. *V* and *PE* showed large spatial variability across the globe as well as in different depths. In topsoil, *V* is high in middle and low latitudinal humid regions, while the spatial pattern trends to uniform with the increase of depth. The *PE* is stronger in warmer and wetter regions. In the soil profile, the *PE* is stronger in upper layers than in deeper layers. Precipitation was the most important for influencing the global pattern of *V* in the topsoil (0-20 cm), while the importance of SOC and bulk density increased in subsoil. Precipitation and temperature were key determinants for PE.

Applying the models across the global, we assessed the response of SOC to 2℃ global warming and 20% net primary production (NPP) increase at the resolution of 1 km. Compared with the model considering *PE* and *V*, the model considering *PE* only significantly underestimated the response of SOC to warming, while the model considering *V* only had no obvious effect on the response. For the response of SOC to the increase NPP, considering *V* only, model overestimated response, while only considering *PE* underestimated response in topsoil.

Our modelling demonstrates the vital roles of vertical carbon transport and priming effect in controlling whole-soil carbon dynamics, which are a key determinants of whole-soil profile SOC persistence under warming.

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Keywords: *Soil organic carbon, vertical carbon transport, warming, priming effect*

Leguminous green manure has the potential for reducing the carbon footprint of crop production

Zhiyuan Yao [a, b, c] and **Yajun Gao** [b]

[a] *Key Laboratory of Mountain Surface Processes and Ecological Regulation, Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, 610041, Chengdu, China*
[b] *College of Natural Resources and Environment, Northwest A&F University, 712100, Yangling, China*
[c] *Department of Soil Science, University of Saskatchewan, S7N 5A8, 51 Campus Drive, Saskatoon, Canada*
Email: zyao@imde.ac.cn

Abstract: Climate change is one of the biggest challenges globally, it is emergent to establish future-oriented strategies to reduce greenhouse gas (GHG) emissions. Intensified crop production has depleted soil organic carbon stocks (SOCS) of the land around the world, therefore, field management practices that can effectively recover the SOCS could be useful to reduce CO_2 concentration in the atmosphere and mitigate climate change.

Growing leguminous crops as green manure (LGM) during fallow period can minimise the use of extra synthetic N fertilizer compared with non-legume crops due to the unique biological N fixation. More importantly, the LGM is N rich and narrow in C:N ratio, introducing it to the cropping system can increase the SOCS with high efficiency. Therefore, the LGM may hold the key to mitigate climate change.

Although other field management practices (*e.g.*, the application of animal manure) can increase the SOCS, they may also increase the GHG emissions from other sources, which make them less effective to control climate change. In addition, the SOCS have limited capacity to increase as they reach the new equilibrium after a long period of time. These aspects indicate that traditional field experiment alone can hardly provide robust information to estimate the performance of field management practices on climate.

To solve the abovementioned problems, we coupled life-cycle assessment to include the GHG emissions from the main agricultural inputs and the RothC model to project the carbon sequestration potential of the SOCS at the new equilibrium. The changes of both the SOCS and the GHG emissions from different agricultural inputs are calculated as the carbon footprint to assess the potential impacts of the LGM on climate. We chose three widely available legumes (Huai bean, soybean and mung bean) as the LGM to replace the traditional summer fallow on the Loess Plateau of China to evaluate their impacts on climate via the carbon footprint.

The LGM treatments significantly increased the annual C input to soil by 67-91% and the corresponding SOCS were increased by 15-23% compared with the control (summer fallow) after 8 years. The LGM treatments increased the GHG emissions from agricultural inputs, however, when the increased SOCS were considered, the carbon footprint ranged from 1370-2091 kg CO_2 eq ha^{-1}, which was 25-51% lower in comparison with the control. The RothC model indicates that the projected SOCS at the new equilibrium for the LGM treatments and the control are 38-47 and 14-18 Mg ha^{-1}, respectively. The corresponding carbon footprint for the LGM treatments will be 53-62% lower than the control and 23-37% lower than their current levels.

Growing LGM during summer fallow period can effectively increase the SOCS and decrease the carbon footprint of crop production. When considering the carbon sequestration potential in the future, the carbon footprint can be further reduced. These results indicate that using the LGM to replace traditional fallow practice could be an efficient alternative to mitigate climate change by reducing the GHG emissions of dryland crop production.

***Keywords**:* *Legume, cover crop, RothC model, life-cycle assessment, greenhouse gases*

An analysis of the spatial distribution of Western Flower Thrips within strawberry polytunnels

Chathurika K. Amarathunga [a], **Hazel Parry** [b], **John Grundy** [c] **and Alan Dorin** [a]

[a] *Department Data Science and AI, Faculty of Information Technology, Monash University, VIC, Australia,* [b]*Agriculture and Food, CSIRO, EcoScience Precinct, QLD, Australia,* [c] *Humanise Lab, Department of Software Systems and Cybersecurity, Faculty of Information Technology, Monash University, VIC, Australia*
Email: don.amarathunga@monash.edu

Abstract: The Western Flower Thrip *(Frankliniella occidentalis)* (WFT) is a major insect pest for Victorian strawberry growers and is typically controlled using biological control agents (e.g., predatory *Orius tantillus* and *Neoseiulus cucumeris*). The simulation of WFT populations may help farmers to quantify the spatial and temporal dynamics of WFTs and can be used as a prediction tool in decision support. Simulating WFT population dynamics requires modelling temperature effects, host plant stage, predators and other field conditions impacting the WFT population. Model parameters can be derived from experiments documented in the literature, however, reported values may not be specific to strawberries as parameters depend on the host plant and experimental setups. Consequently, fine-tuning parameters requires data specifically collected from strawberry farms. Since the appropriate spatial scale to model thrip populations is unknown, to develop a WFT population dynamic model for semi-protected strawberry crops, we collected preliminary data from a farm at multiple spatial scales to explore WFT population spatiotemporal dynamics.

Our field site was a strawberry farm in Victoria, Australia. We studied two multi-polytunnel planting blocks (I and II) approximately 1km apart separated by light vegetation and weeds. Flower samples were collected from polytunnels fortnightly for 21 weeks to record the number of WFTs per flower. Initial results appear to show similar numbers of WFTs at the middle of a polytunnel and its edges (Figure 1a). Comparison between blocks I and II reveals that WFT counts per flower may vary between blocks (Figure 1b). Hence, further statistical analysis, and perhaps data, will be required to understand the optimal spatial scale of a population dynamic model to reflect differences between finer spatial scales (e.g., block-level). We then compared our data with WFT counts reported as a range (Low 0-5, Medium 5-10, High >10) by an industry monitoring expert who visually inspected random flowers but also targeted sampling at potential hotspots. Our results show the current industry monitoring process seems to overestimate WFT numbers near the end of the flowering season (Figure 1b). This may be due to the industrial process' bias towards sampling from hotspots. Hence, it will be important to enhance understanding of biological explanations for increasingly patchy WFT populations in polytunnels and to incorporate such factors into thrip population models with the help of data collected from multiple sources.

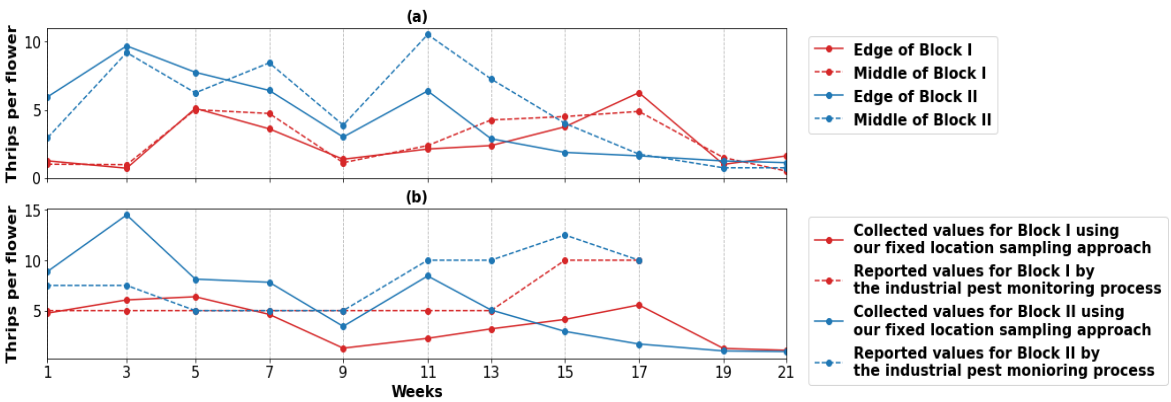

Figure 1. Variation of the number of WFTs per strawberry flower over the period 15 Dec 2020 to 05 May 2021. (a) Polytunnel edge vs middle; (b) WFT counts from our fixed location sampling data vs industrial hotspot-seeking pest monitoring

Keywords: *Western Flower Thrips, strawberry crop, spatial model, integrated pest management, insect*

Models and realities: Iterative refinement and understanding in agent-based models of honeybee perception and action

Alan Dorin[a], Tim Taylor[a] and Adrian Dyer[b]

[a] Dept. of Data Science & AI, Faculty of IT, Monash University, Clayton 3800, Australia
[b] School of Media and Communication, RMIT University, Melbourne 3001, Australia
Email: alan.dorin@monash.edu

Abstract: This paper explores issues arising from the complexity of integrating data into spatial agent-based models (ABMs) of honeybee flower visitation to generate short individual foraging movements "bottom-up". A simple method to simulate such movement diffuses a population across a region. Individuals are not distinguished and dispersal occurs at empirically determined rates constrained by habitat envelope parameters. Since honeybees are excellent learners whose visual capabilities, movements and decision-making are heavily informed by individual experience and social communication (Avarguès-Weber and Giurfa 2014), for much pollination-related research these kinds of aggregate models are unsuitable and ABMs are preferred.

If individual-level bee movement is required, it can be approximated by Brownian motion within physiological and environmental constraints. A more complex approach integrates amalgamated data from field observations, animal tracking or optimal foraging theory to generate statistically plausible insect trajectories via a biased random walk or Lévy flight (Waddington 1980, Reynolds and Rhodes 2009, Bukovac, Dorin et al. 2013). Key parameters include speed, directional variability, and tendency to seek/flee landscape features like resources, refuges, predators, mates or sunlight. In this case, model parameters must vary based on bee task allocation.

Arguably the most complex but realistic bee-ABM represents perceptual and cognitive processes based on data from field and psychophysics experiments with honeybees to generate bee movement from scratch. But, despite detailed knowledge on bee psychophysics, how decision-making, learning and memory interact in complex multifactorial environments remains largely unknown and poses deep conceptual and philosophical difficulties.

Here, we unravel the complexity of interactions between the real world as understood and perceived by: us; honeybees; and the real world as perceived by bees as it is partially understood by us and represented in simulations whose results we interpret to understand bee perception and cognition. This is a convoluted, multilevel set of reality-model-theory interactions since theories of bee perception are insufficiently independent of the model to allow us to simply collect and feed empirical data in as parameters. Although the models we describe simulate bees' foraging decisions bottom-up with parameters derived from empirical data on bee visual perception, flower memory, flower constancy, innate colour preferences and learning, the simulation results force us to iteratively refine our understanding of the perceptual and cognitive process that generate the very phenomena we simulate and parameterise. This causes constant re-evaluation of what empirical data tells us about how bee perception impacts bee cognition and decision-making. Hence, this ABM development process iteratively refines our understanding of "bee reality" and key plant-pollinator interactions.

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Keywords: *Agent-based model, pollinator, honeybee simulation, insect perception*

INVITED PAPER

EXTENDED ABSTRACT ONLY

Using tracking data of animal movement: how to deal with personalities and contingencies?

Volker Grimm[a]

[a] *Department of Ecological Modelling, Helmholtz Centre for Environmental Research-UFZ, Leipzig, 04318, Germany*
Email: volker.grimm@ufz.de

Abstract: Movement is a key process in ecology, affecting the fate of individual organisms, populations, communities and ecosystems. Modern tracking techniques provide new data for parameterizing, testing and using individual-based movement models. However, for many species the number of successfully tracked individuals and the observation times are still limited. This makes modelling still challenging, because individual movement paths have been shown to often depend on animal personalities and on behavioural and environmental contingencies. As an example I will discuss an existing model of the Saimaa ringed seal (*Pusa hispida saimensis*), which is endemic in a lake in Finland and threatened due to small population size and fishing-induced mortality (Liukkonen et al. 2018). With data from five individuals, it was impossible to develop a single calibration of the model. The movement model was therefore re-calibrated, using the pattern-oriented approach (Grimm and Railsback 2012), for each of the five individuals. As a consequence, for using the model for addressing management and conservation questions, parameters will have to be taken from probability distributions. I will briefly discuss further examples and possible general solutions to the challenges posed by contingencies and animal personalities.

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Keywords: *Ecology, movement, tracking data, animal personalities, agent-based modelling, pattern-oriented modelling, seals, Pusa hispida saimensis*

Parametrisation and validation of a mechanistic individual-based distribution model for the red kite *(Milvus milvus)* in Switzerland

Anne-Kathleen Malchow [a], Guillermo Fandos [a], Urs Kormann [b], Martin Grüebler [b], Marc Kéry [b], Florian Hartig [c] and Damaris Zurell [a]

[a] Institute of Biochemistry and Biology, University of Potsdam, 14469 Potsdam, Germany, [b] Swiss Ornithological Institute, 6204 Sempach, Switzerland, [c] Faculty of Biology and Pre-Clinical Medicine, University of Regensburg, 93053 Regensburg, Germany.
Email: malchow@uni-potsdam.de

Abstract: The red kite *(Milvus milvus)* is an iconic bird of prey in Europe. It is endemic to the western Palearctic and occurs mainly in the temperate and the western Mediterranean zones of Europe. After it had suffered overall population declines during 1990-2000 of almost 20% throughout its range (BirdLife International 2004), the red kite has seen accelerating increases in recent years. During the 1980s and 90s, the main part of the global red kite population was located in Germany, France and Spain, but countries like the U.K., Sweden, Poland and Switzerland have since gained importance due to rapid increases. Still, large inhomogeneities in the spatial distribution and population trends of the species exist. Thus, it is crucial to know which key factors determine the red kite's distribution on finer scales, especially within its core range, to effectively inform its global conservation and management.

In order to understand the mechanisms underlying the red kite's spatio-temporal dynamics in Switzerland, where the population size has been steadily increasing during the past three decades, we configure an individual-based mechanistic distribution model (IBM) using the modelling platform *RangeShiftR* (Malchow et al. 2021; https://rangeshifter.github.io). In comparison to the much more commonly used correlative species distribution models (SDMs), such mechanistic models offer important advantages: they don't assume that the observed distribution is in equilibrium with the environmental conditions and they can factor in the effects of dispersal limitations and source-sink dynamics (Guisan & Thuiller 2005) by explicit consideration of dispersal. Our IBM's model parameters are calibrated from two sources of information merged in a Bayesian inference approach: they are informed directly using prior knowledge of the species' ecology as well as inversely using abundance data from the Monitoring of Swiss Breeding Birds program (Schmid 2004). Our results suggest that the survival rate of chicks in the first year plays an important role in the population dynamics of the red kite and that there is potential for further increases in the Swiss population. In order to assess the transferability of our model's projections to other regions and into the future, we perform a spatial block cross-validation with the configured IBM. In this approach the hold-out data of each validation fold represents a contiguous geographic region and can thus serve as an imitation of environmental extrapolation.

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Keywords: *Species distribution dynamics, spatially-explicit simulation models, individual-based models, Bayesian inference, cross-validation*

Does memory help optimise fruit fly foraging at the landscape level?

Jaye D Newman[a,b], **Anthony R Clarke**[a], **Rehan Silva**[a] **and Hazel Parry**[b]

[a] *School of Biology and Environmental Science, Queensland University of Technology, Brisbane, QLD 4001, Australia*
[b] *CSIRO, GPO Box 2583, Brisbane, QLD 4001, Australia*
Email: jaye.newman@qut.edu.au

Abstract: Remembering a good quality diet or patch generally has positive implications for fitness for animals, though there may be circumstances where memory could become detrimental. In the polyphagous pest insect *Bactrocera tryoni* (Froggatt) recent research indicates that memory contributes to their foraging strategy. When presented with a good quality host in which to lay eggs they will remember that host for a longer time than a poor host. Though when presented a poor host, the preference the following day will be for the poor host even if the good host is present, but this memory will decay quickly if they do not receive continual exposure. We wanted to know how optimal foraging strategy with and without memory would influence population and time spent in three host quality types: good, average, and poor in a local heterogeneous landscape context. An individual-based population model was developed to examine how these behaviours respond in four heterogeneous landscapes with host proportions of 30% and 60%, fragmented or aggregated. There were also three fruiting scenarios: simultaneous, or sequential with good host type fruiting first, or poor host type fruiting first. The mean daily population was similar between the different landscapes, except when fruit was available simultaneously and fragmented with 60% proportion of the landscape hosts where optimal foraging fly population was much higher than fly agents with memory. When fruits were available simultaneously the fly agents that had memory spent more time in poor and average hosts than the fly agents with optimal foraging behaviour. When hosts were fruiting sequentially there was little difference between the time spent in each host type. This is an interesting first look into incorporating memory mechanisms into an individual-based model using data from a polyphagous pest.

Keywords: *Memory decay, ecological modelling, agent-based, foraging*

Validating a spatially explicit bark beetle dispersal model with infestation patterns from a national park in Germany

Bruno Walter Pietzsch[a], **Felix Johannes Peter**[b] **and Uta Berger**[a]

[a]Department of Forest Sciences, Institute of Forest Growth and Forest Computer Sciences, Technische Universität Dresden, Tharandt, Germany,
[b]Abteilung Waldschutz, Forstliche Versuchs- und Forschungsanstalt Baden-Württemberg, Freiburg, Germany
Email: bruno_walter.pietzsch@tu-dresden.de

Abstract: The timely removal or debarking of infested trees is considered to be the most efficient counter measure to protect forests from the spread of infestations by the European Spruce Bark Beetle (*Ips typographus* L.). For this reason, this so called sanitation felling is applied to protect forests with economic purposes from bark beetle infestations originating from areas without management intervention such as national parks. To investigate the effectiveness of this measure against bark beetle dispersal, the existing Individual-based model on *Ips typographus* IPS (Kautz et al. 2014) was upgraded to facilitate GIS data import and applicability in real forested landscapes.

The newly developed model IPS-SPREADS (Infestation Pattern Simulation Supporting PREdisposition Assement DetailS) was validated by reproducing four infestation patterns from the Saxony Switzerland national park, Germany, as recorded in the years 2015, 2016 and 2017, where a mass outbreak within the protected area took place. For this, trees infested in the year before were used as beetle source trees and trees infested during the investigated year as targets for the model validation. The reproduction of the exact same location of infested trees proved to be challenging, resulting in nearly the same amount of falsely infested trees. Nevertheless, as the correct amount and direction of infestation spread was easily reproducible, the application of IPS-SPREADS for investigating the impact of management measures on the bark beetle dispersal was feasible.

The proposed presentation will highlight the challenges and success stories accompanying the reproduction of infestation patterns during a mass outbreak as was done to find meaningful parameter values during model validation. It will focus on the methods applied and on the discussion of the results of this pattern reproduction with findings from other empirical and simulation studies.

The model IPS-SPREADS and its validation were recently published in Frontiers in Forests and Global Change (Pietzsch et al. 2021).

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Keywords: *Ips typographus, model validation, spatial pattern reproduction, agent-based model, individual-based model*

Spatial modelling of cross-pollination in crop systems through multi-point honeybee tracking

Malika Nisal Ratnayake [a], Adrian G. Dyer [b c], Alan Dorin [a]

[a]*Computational and Collective Intelligence Group, Dept. of Data Science and AI, Faculty of Information Technology, Monash University, Victoria, Australia*

[b]*School of Media and Communication, RMIT University, Victoria, Australia*

[c]*Department of Physiology, Monash University, Victoria, Australia*
Email: malika.ratnayake@monash.edu

Abstract: Global food demand is forecast to increase by 56% from 2010 to 2050 (United-Nations, 2019). To ensure food security and meet the demands of the 21^{st} century, production needs to increase yields and become more resilient and sustainable (FAO, 2018). Crop protection under greenhouses and polytunnels helps boost food production in an increasingly unpredictable climate. Insects, such as bees, are managed widely in these controlled environments to facilitate pollination. Hence, spatial models can potentially be helpful to understand complex bee-plant pollination interactions to improve crop yield.

Since cross-pollination affects crop yield and can improve the quality of a fruit set, different crop varieties are planted in adjacent rows to encourage it. However, managed pollinators such as honeybees have been observed to follow rows in several cropping systems (MacInnis and Forrest, 2020), minimising the potential for cross-pollination, and potentially contributing towards a low-quality fruit set.

Spatial simulations of bee behaviour can be used to investigate the row-following behaviour of bees (Dorin et al., 2018). Camera observations help to build such spatial models as they can record the spatiotemporal variations in bee behaviour. We therefore deployed a multi-point camera system to detect whether or not managed honeybees (*Apis mellifera*) did in fact follow rows in an industrial strawberry farm in Victoria, Australia. The multi-point system consisted of nine camera units placed along the edges and middle of strawberry polytunnels. We collected data for six days during the peak activity period of pollinators. Recorded videos were then processed automatically (Ratnayake et al., 2021) to extract movement data of 1805 honeybees to analyse their row-following behaviour.

Our analysis showed that 85% of the recorded tracks across all locations within the polytunnels were not row-following. The general directionality of honeybees varied with location and time of day. Our system will provide models with individual-level bee movement data enabling behavioural parameters in the model to be modified in near-real-time (An et al., 2021), helping growers to determine which planting arrangements would improve cross-pollination and crop yield. Furthermore, our system is useful in further investigating different types of honeybee behaviour to uncover new findings for ethology.

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Keywords: *Deep-learning, agriculture, pollination, monitoring, computer-vision*

Biosecurity and forestry pest modelling for the Green Triangle

Anna Weeks[a], **Kathryn Sheffield**[b], **David Smith**[c,d] **and John Weiss**[b,d]

[a] *Agriculture Victoria Research, 124 Chiltern Valley Road, Rutherglen, VIC, Australia; 3685*
[b] *Agriculture Victoria Research, AgriBio, 5 Ring Road, Bundoora, VIC, Australia 3083*
[c] *Agriculture Victoria, Office of the Chief Plant Health Officer, 2 Codrington Street, Cranbourne, VIC, Australia. 3977*
[d] *School of BioSciences, University of Melbourne, Parkville, VIC, Australia 3010*
Email: anna.weeks@agriculture.vic.gov.au

Abstract: This paper looks at forestry production systems, how they respond to different climates and landscapes, and how exotic pest species can become established and spread through these environments. What would happen if an exotic pest breached border biosecurity and became established in our forests? What would be the impact on the trees, how quickly would it spread, could we eradicate it altogether and how much would it all cost? These are some of the questions we want to answer as part of the NIFPI project "Innovative Forest Health and Biosecurity for the Green Triangle".

The approach we have applied to this task is novel and unique in that it attempts to define the connected relationships between each point of the disease triangle; that is, the environment, the host tree, and the pest over time. On one side, we have a forest model that captures the tree growth response and allows us to account for water-stress and nutrient deficiency. On the other side, we have an agent-based pest model that captures the human and environmental factors that influence the pest development and dispersal. As the pest spreads, we then consider the impact of the pest on tree growth and health over time.

So, who are the villains in this piece? Consider the longhorn beetle, *Monochamus alternatus*, host to a deadly nematode that releases a toxin that stops the sap flow in a tree. Within ten years of the first detection in Portugal, over 30% of the pine plantations had died. The EU now maintains a 25km aerial surveillance buffer around the entire country. Other pest-species considered include the Asian gypsy moth, pine beetle, and myrtle rust, which have similarly frightening back-stories.

With an economic overlay, our modelling lets us assess the costs of an exotic pest outbreak to an Australian industry worth more than 9 billion dollars. This includes cost associated with lost wood production, quarantine requirements, market restrictions and biosecurity surveillance. In doing so, we can also start to quantify the benefits of early detection, ongoing surveillance, and monitoring programs. As this project draws to a close, there is significant interest in taking this approach to a national level and expanding the model to include endemic pests and the changing response of both host trees and pests to climate change.

Keywords: *Dispersal, insect pest, surveillance, host suitability, pest impact*

Changing crop management improves farm level productivity and profitability for smallholder farmers in northern India

Y.G. Beletse [a], **A.M. Laing** [b], **D.B. Prestwidge** [b], **M.K. Gathala** [c], **N. Subash** [d] **and A.C. Liedloff** [e]

[a]CSIRO Agriculture & Food, Canberra, ACT; [b]CSIRO Agriculture & Food, Brisbane, Qld 4067, Australia, 2601, Australia; [c]CIMMYT, Dhaka, Bangladesh; [d] ICAR Meerut, Uttar Pradesh, India; [e] CSIRO Land & Water, Darwin, NT 0822, Australia
E-mail: yacob.beletse@csiro.au

Abstract: Cropping practices such as diversification, intensification and conservation agriculture-based management, which provide productivity and economic benefits to farmers, have been tested across northern India; however, farmers' adoption rate of these technologies remains low. A key reason for poor adoption rates of improved practices is the difficulty in enabling farmers, extension officers and policymakers to understand the likely farm-level trade-offs and benefits of these practices. Simulation models which integrate resources and activities (i.e. crop and livestock production, economics, and labour availability) across the whole farm can be used to examine the trade-offs and benefits of alternative farming systems. This study examined changes in farm-level productivity and profitability over a 20-year simulation window under a range of cropping system interventions for four farm typologies found in smallholder farming systems across the northern Indian cereal-growing belt. The farm typologies studies are: well-resourced, moderately-well resourced, moderately-poorly resourced and poorly-resourced farming systems. The baseline management for each farm typology was a rice-wheat cropping system under conventional crop management practice combined with dairy production. Alternative cropping system scenarios were (1) intensification (inclusion of a third crop, mungbean); (2) diversification (replacing wheat with maize); (3) intensification and diversification combined (intercropping spinach with maize); and (4) introducing conservation agriculture (CA) management practices in all cropping systems. The same livestock management was maintained in all scenarios, with mating of cows staggered throughout the year to try to maintain continuous milk supply. The effects of intensification and CA were examined for all four typologies; diversification and intensification-and-diversification combined were examined for the two more marginal typologies only. For all scenarios, farming system economic productivity, gender-disaggregated labour requirements, and the farm cash balance were simulated monthly and then reported annually. Intensifying the cropping system increased farm economic productivity by 16-19%, diversification increased productivity by 21-40%, intensification combined with diversification increased farm economic productivity by 19-39%, and CA practices improved economic productivity in all combinations of cropping system scenario and farm typology. CA practices reduced overall farm labour requirements, with savings greater for men than for women. Diversification did not affect labour demand, while intensification increased labour requirements, especially for men. Annual farm cash balances increased when cropping systems were intensified by introducing a third consecutive (mungbean) or concurrent (intercropped spinach) crop and in cropping systems under CA practices. This study demonstrates the ability of biophysical whole-farm models to quantify the likely medium-term effects of a range of cropping system management options in terms of farm economics and labour requirements. This simulation modelling approach has the potential to enable farmers, extension officers, policymakers and others to examine the benefits, risks and trade-offs of different management options within smallholder farming systems.

Keywords: *CLEM, conservation agriculture, intensification and diversification, farming systems, simulation modelling*

Building responsive bio-economic models to replicate complex farm management decisions for mixed irrigation farming systems in southern NSW

K. Broadfoot[a], **M. Cashen**[b]. **K. Behrendt**[cd], **A.J. Clark**[a] **and P. Graham**[e]

[a] NSW Department of Primary Industries, Orange Agricultural Institute, 1447 Forest Road, Orange, NSW, [b] NSW Department of Primary Industries, Wagga Wagga Agricultural Institute, 322 Pine Gully Rd, Wagga Wagga, NSW 2800, [c] Graham Centre for Agricultural Innovation, Wagga Wagga, NSW 2800, [d] Harper Adams University, Edgmond, Shropshire, UK, TF10 8NB, [e] Graham Advisory, 78 Obrien St Yass, NSW, 2582. Email: kim.broadfoot@dpi.nsw.gov.au

Abstract: This paper is part of a broader study that uses AusFarm, a complex biophysical model, to model a mixed irrigation farming system in the Murray Irrigation Area and Districts (Murray Irrigation Limited (MIL) post 1995). The study is unique is that the biophysical model has been coupled to an economic module that includes an irrigation sequence model and pricing function. The study has enabled the examination of water market tools that irrigators have available to them in the MIL ('temporary water' and 'carry over'), and the importance of these tool in managing future risk under changing climates.

This paper shows that a combination of water market tools will be an important component in managing risk under changing climate, at least under a mid-range emissions scenario with modest reductions in irrigation water availability. For example, the modelling in this paper shows that having both the ability to carry over water to the following water year, and access to temporary water markets increases the likelihood of sowing opportunities and yield gains for the summer irrigated crop for both historical and projected climate periods. Access to these tools will become crucial as irrigators manage future water supply and demand risk under the impact of climate change and changes to water policy.

Keywords: *AusFarm, climate change in agriculture, agricultural systems modelling*

A bioeconomic model for the identification of sustainable grassland management strategies under climate change

A. Kaim [a], C. Boos [b], T. M. Schmitt [a], R. Kiese [b] and T. Koellner[a]

[a]*Professorship of Ecological Services, University of Bayreuth, Nürnberger Straße 38, 95447 Bayreuth, Germany*

[b]*Karlsruhe Institute of Technology, Institute for Meteorology and Climate Research, Garmisch-Partenkirchen, Germany*

Email: andrea.kaim@uni-bayreuth.de

Abstract: Grasslands cover more than a third of the European Union's (EU) agriculturally used area. Next to being a hotspot for biodiversity, they provide important ecosystem services (ES), e.g. fodder production, carbon sequestration, erosion regulation or recreation. However, grassland ecosystems are threatened due to land-use intensification, land abandonment, and conversion to cropland. Additionally, climate change may have positive (e.g. longer vegetation period) as well as negative effects (e.g. droughts) on grassland productivity. Thus, one of the main challenges is the identification of sustainable grassland management strategies that guarantee the long-term provisioning of important ES under climate change. We address this problem by developing a bioeconomic model that accounts for biophysical as well as socioeconomic factors simulating the effect of climate change and organic N fertilization on ecosystem services.

For this purpose, two sub-models – an agent-based socioeconomic model and a bio-geochemical model – were coupled. The agent-based model calculates the amount of available organic fertilizer based on cattle numbers, and the field-specific N requirement using remote sensing data on cutting events and soil data. Following restrictions, e.g. due to the German fertilization ordinance, water/nature protection zones and agri-environmental schemes, organic fertilizer is distributed on the fields according to their individual N requirements. The model also includes simple rules for trading organic fertilizer among neighbouring farms. The amount of applied fertilizer and cutting regimes serve as input for the bio-geochemical model, which determines their effect on selected biophysical variables (e.g. yield, C/N dynamics, N losses). In a multi-year run under different climate scenarios, these outputs will again affect management decisions (e.g. reduction/increase of cutting events, changes in cattle numbers). Further, modelling output will include estimations of achieved economic yields based on contribution margins for grassland.

The static (i.e. one year) version of the model has been applied to a (pre-)alpine case study in Southern Bavaria, Germany – an area with a large proportion of permanent grasslands that are mainly used for dairy production. First results show that for the status quo, N requirement of modelled grasslands does not exceed the maximum allowed amount of organic fertilization (i.e. 170 kgN/ha) and can be covered by available organic fertilizer from cattle farming. However, in light of climate change, grassland productivity is expected to increase in specific areas opening up the potential of careful intensification and allowing the reduction of management intensity at other sites that will become less productive. As a next step, these effects will be analyzed with the multi-year version of the model.

The model is validated by experts and results of farmer surveys at different stages. Next to analyzing the effects of climate change and management on grassland ES, it can be used to test innovative policy measures (e.g. changes in the fertilization ordinance). The interdisciplinartiy of the model together with the strong focus on stakeholder integration can help identifying policy-relevant management options that are suitable for real-world implementation. Further, it provides an example of how a socioeconomic agent-based model can be coupled with biophysical models in order to consider the multiple facets of land management within a single modelling framework.

Keywords: *Agent-based modelling, bio-geochemical modelling, grassland management, decision making, fertilization*

The 'cause and effect' of water decisions: Generalizing water production functions for viticulture through biophysical simulation

Matthew J. Knowling [a], **Seth Westra** [a], **Bree Bennett** [a], **Bertram Ostendorf** [b], **Rob R. Walker** [c, d], **Anne Pellegrino** [e], **Everard J. Edwards** [c], **Cassandra Collins** [d], **Dylan Grigg** [d] **and Vinay Pagay** [d]

[a] *School of Civil, Environmental and Mining Engineering, Faculty of Engineering, Computer and Mathematical Sciences, The University of Adelaide, Australia*
[b] *School of Biological Sciences, Faculty of Sciences, The University of Adelaide, Australia*
[c] *CSIRO Agriculture and Food, South Australia, Australia*
[d] *School of Agriculture, Food and Wine, Faculty of Sciences, The University of Adelaide, Australia*
[e] *LEPSE, Montpellier University, INRAE, Institut Agro, Montpellier, France*
Email: matthew.knowling@adelaide.edu.au

Abstract: The uptake of digital agriculture requires that 'cause-and-effect' relationships can be encoded in a mathematical form. A relationship of fundamental importance to irrigated agriculture is that between water application and yield. However, cause-and-effect relationships are often partial, and are challenging to extend to new environments and social-economic contexts. The viticulture industry in particular is currently unable to realize the full promise of digital agriculture due to its sole reliance on empirical field data to derive water production relations.

In this study, numerical experiments are conducted using a process-based crop model (VineLOGIC; Walker et al., 2020a, b) to establish grapevine water production relations that account for both the influence of uncertain exogenous factors (e.g., climate/weather, genetic coefficients, soil permeability) and operational decisions (e.g., intra-seasonal irrigation timing). Case studies representing vineyards of different grape varieties in the Sunraysia and Riverland regions of south-eastern Australia are considered. We explore the generalizability of water production relations and their sensitivity to exogenous factors and operational decisions across these growing seasons and case studies.

Results indicate a largely linear relation between irrigation applied and yield across all experiments, despite significant variance surrounding this relation due to both exogenous factors. However, the influence of exogenous factors on water production relations in relative terms (i.e., change in yield with respect to change in irrigation) is considerably reduced, indicating that relative production relations allow for more robust and generalizable insights. For example, for every one megalitre change in total irrigation, a mean change in yield of approximately three tonnes occurs, with 95% confidence intervals spanning up to approximately eight tonnes per megalitre. Previously reported yield-to-irrigation change values in the literature lie within this interval. The greatest return on water applied was generally found to occur post-veraison. However, findings regarding intra-seasonal irrigation timing effects on water productivity relations appear to be less generalizable, varying between seasons and case studies.

This study demonstrates how process-based modelling can be used to achieve generalized cause-and-effect relations between water application decisions and production outcomes at a resolution that is decision-relevant, throughout the season, and in the face of uncertainty. With such advances, the potential of digital agriculture technologies can start to be better realized in industries like viticulture, benefitting growers through easy-to-use tools to achieve improved water management decision making.

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Keywords: *Digital agriculture, water production function, crop model, viticulture, decision support*

Boeing CST-100 Starliner Virtual Reality Demonstration

Christopher Galea and **Nathan C Perry**

Boeing Research & Technology Australia
Email: christopher.p.galea@boeing.com

Abstract: The Boeing Research & Technology Australia (BR&T-A) Interactive and Immersive Technology Team have successfully developed a world leading virtual reality (VR) approach for spacecraft simulation. The technology has been demonstrated to NASA and a public version was first showcased at the world's largest space conference, the International Astronautical Congress (IAC) in 2017.

Full motion simulators and even fixed based simulators are very expensive, consume large footprints and require crew to travel to a particular site for training. Furthermore, in relation to space missions, crew may not have access to simulated flights or emergency procedures for periods of 6 to 9 months and then need to perform re-entry procedures (e.g. while on board the International Space Station (ISS) or a future Mars mission). VR provides a cost effective and high fidelity solution to these challenges and has a wider range of beneficial applications for our space, defence and commercial businesses. BR&T-A has been able to assemble a full VR production team unlike anything elsewhere in Boeing. It includes: psychologists / human factors experts, 3D design specialists (recruited from the gaming industry), VR experts and back-end simulation experts.

The CST-100 VR simulator with high resolution graphics was created by the BR&T-A Interactive and Immersive Technology team in concert with Boeing Houston and CST-100 astronauts who provided ongoing feedback on key training aspects of the early model. The public version of the model that will be demonstrated in the MODSIM2021 presentation shows the functionality of the CST-100 docking procedure with the ISS.

The BR&T-A team has achieved a commercial grade resolution and expandable solution for the CST-100 VR simulator that has also been used for numerous STEM outreach initiatives with the aim of stimulating the next generation of young scientists and engineers interested in a career in the aerospace industry. The team is supporting additional VR design and training initiatives for the NASA Artemis mission to return to the moon by 2024 and the NextSTEP Moon to Mars mission over the longer term.

Keywords: *Virtual reality, Immersive technology, Advanced simulation & training, STEM outreach*

Digital twins as learning environments for catchment and water resource management

Joseph Guillaume [a], **Angus Dunne** [a,b], **Laura Fisher** [b], **Niilo Gobius** [c], **Natasha Harvey** [a] **and Wendy Merritt** [a]

[a] *Institute for Water Futures and Fenner School of Environment & Society, The Australian National University, Canberra, ACT 2601, Australia*
[b] *The Mulloon Institute, Bungendore, NSW*
[c] *Gulf Savannah NRM, Mareeba, Queensland*
Email: joseph.guillaume@anu.edu.au

Abstract: In the context of catchment and water resource management, digital twins are far from being able to be copies of the physical world given the large amounts of expensive data required and substantial uncertainty involved. Instead, it makes sense to emphasise the process of digital *twinning*, through which the digital twin is accepted from the start as being uncertain and imperfect. Completion of twinning is seen as a theoretical aspiration under which prioritising and reducing uncertainties over time is valued as a means of gradually improving system understanding and performance within a data-driven organisation or community.

A digital twin remains a time-varying representation of a system that brings together observed information and predictive model capabilities. It provides a structure within which to accumulate information and understanding, identify uncertainties and gaps, and reason about the value of new information, in addition to reasoning about potential improvements to system operation.

In contrast to typical modelling practice, the digital twin aspires to be a perfect representation of all aspects of an interconnected system. The digital twin is intended to be an oracle that provides answers to any question without limit – the futility of this aim emphasises that every measurement and model prediction is only an estimate, and feeds into deliberation about potential investments to fill gaps or improve estimates. The role of measurements is not just to be integrated into modelling in a data assimilation framework, but rather to provide independent estimates within the context of an uncertain oracle. Photo monitoring and landholder experiences are treated as equally valid sources of knowledge within the digital twin, which takes on the role of a learning environment in which multiple knowledges and sources of spatiotemporal information are integrated within a multi-scale conceptual model of the system.

The digital twin becomes a boundary object to facilitate knowledge governance through debate about knowledge rather than just using knowledge, and for uncertainty prioritisation and investment planning rather than providing the last word on any topic. This presentation draws on valued collaborations with Murrumbidgee Irrigation, The Mulloon Institute, as well as with Gulf Savannah Natural Resource Management in a project funded by the Queensland Water Modelling Network (QWMN).

Keywords: *Digital twin, uncertainty prioritisation, knowledge governance, catchment management*

Mechanical digital twinning of the human body in the workplace for reduced injury risk and improved health

S. M. Harrison and **R. C. Z. Cohen**

CSIRO Data61, Clayton VIC
Email: Simon.Harrison@csiro.au

Abstract: A digital twin (DT) is a virtual model that acts as a mirror of its physical counterpart that may be solely a replication of certain features of the physical twin, or it may also include the ability to simulate potential future states. The fusion of data from the real world with the virtual model requires the use of sensors and processing of sensor data for inclusion in the digital representation. Simulation capabilities of the DT must be of sufficient detail to accurately forecast the effect of proposed system changes. Usability of the DT for operational tasks depends on the quality of the aforementioned requirements plus the clarity in which the state of the DT is presented to the user.

Here we describe development of a human digital twin (HDT) pipeline for predicting injury risk during workplace activities. The system comprises a set of cameras (typically cheap webcams), a GPU enabled computer, and an in-house developed software package called "Ergomechanic". Figure 1 shows an example visualisation of the HDT for a participant performing a manual handling task. The software combines markerless motion capture (MMC) with biomechanical modelling to calculate the pose of each worker's body and the loading upon major body components. Extremes in movement speeds and loading can be predicted and related to injury risk. Metrics defining injury risk can be improved and refined by wider spread use of the technology and correlation with recorded injuries. Example uses of the system to measure workplace activities and body loading are described. Future extensions of the system are discussed, such as viewing outputs in Augmented Reality (AR).

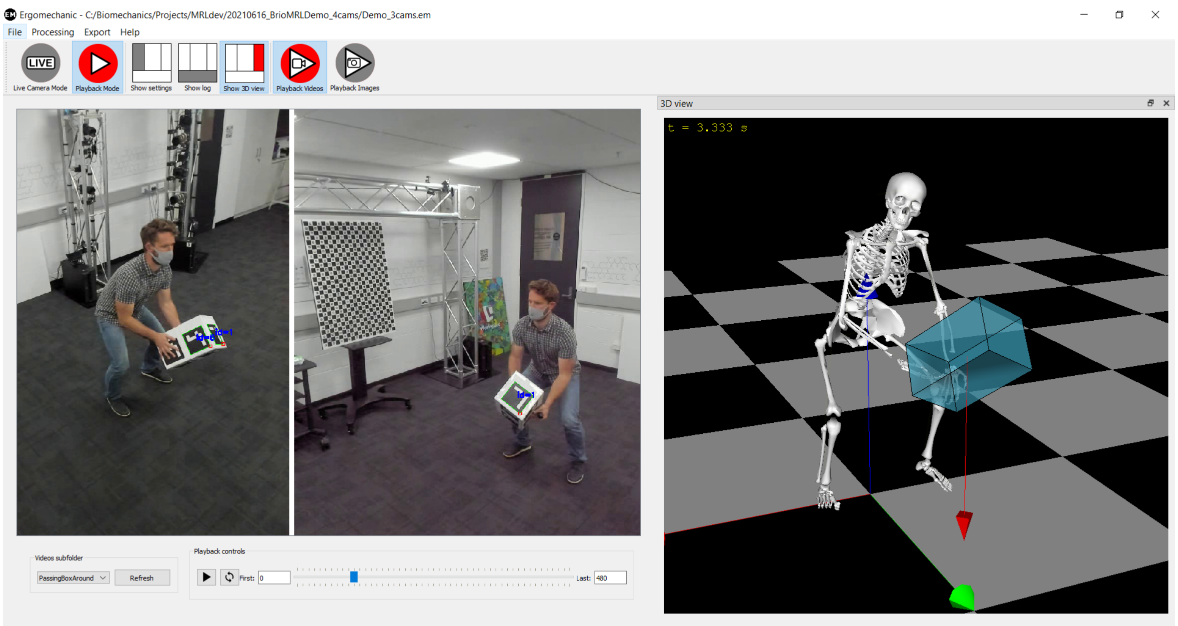

Figure 1. Example interface for the Human Digital Twin (HDT) using the Ergomechanic software

Keywords: *Digital twin, ergonomics, injury, biomechanics, motion capture*

Continuous monitoring of subsurface injections using tiltmeter sensors

Dane Kasperczyk [a] **and Dang Quan Nguyen** [b]

[a] CSIRO Energy, Melbourne, Victoria. [b] CSIRO Data61, Melbourne, Victoria.
Email: dane.kasperczyk@csiro.au

Abstract: The need to injection fluid and/or gas underground is required for several industries and used for purposes such as carbon sequestration, hydrocarbon recovery, mine preconditioning, seismic mitigation and energy storage. Monitoring this subsurface injection is important to ensure effective results, for example, if carbon dioxide pumped for sequestration migrates from predicted storage locations it would be an ineffective outcome and remedial action may be required. In some instances, regulatory approval for operations may require a specific environmental plan that can use monitoring as a control. Having an understanding of the state of the subsurface is invaluable for correct decision making and operation.

Monitoring the injection in-situ is difficult to impossible, but, there are some remote sensing techniques such as fibreoptics, tiltmeters and geophones (microseismic) that can be used. Tiltmeters are highly sensitive sensors that can be placed far from the injection location that measures the tilt flux field associated with subsurface injections down to less than 5 nano-radians. Using an array of tiltmeters and by providing the tilt response and known geospatial data to an inverse model it is possible to resolve the injection volume and plane of injection, and with more advanced algorithms ability to model the progressing fluid front (Lecampion et al 2005).

Subsurface injections can be hundreds or thousands of metres deep meaning the only feedback operators may have natively are injection pressure and injection rate. To provide meaningful actionable data the current state of the subsurface needs to be visible to an operator or to be available as an input to an automated injection system. Using the tiltmeters data in a real-time feedback loop is one method to provide this data and has been implemented in this case study.

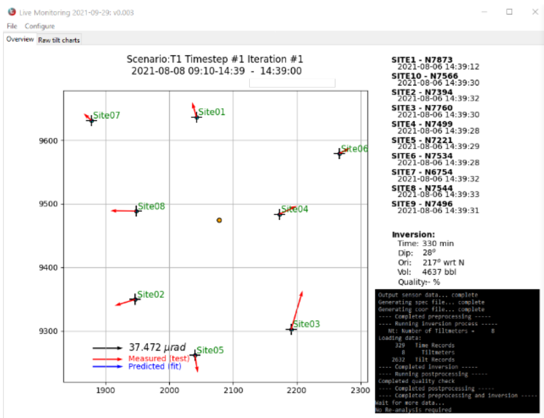

Figure 1. FracturaLive tiltmeter monitoring

To create a digital system that provides information about the current subsurface tiltmeters and models have been coupled in a continuous workflow. The modelling platform, *Fractura* (Kear et al. 2019), is used with a mesh wireless sensor network (Sourosh and Mow 2019) and an automated data workflow. The wireless sensor network relays signals from the sensors to a central node that runs signal processing steps in denoising and detrending. Once a settable threshold of sensors have transmitted data a selected *Fractura* model processes it and the results are fed back into a GUI and database for action. This can be run on a set interval or continuously with each run pulling the most up-to-date data depending on the required operation.

The live monitoring has been deployed at several sites and is still in the early stages of use. So far this platform is a useful advancement to provide better feedback for automation and operational decision making. This specific use case of the digitally representing a part of the subsurface can be further improved by coupling with additional sensors and expanding the state tracking between injections.

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Keywords: *Software platform, real-time monitoring, automated workflow*

Using Workspace to implement Digital Twins in the Mixed Reality Lab

Damien Watkins[a], **Matt Bolger**[a], **Lachlan Hetherton**[a], **Zikai Zhang**[a], **Ping Xie**[a], **Simon M. Harrison**[a] **and Raymond C. Z. Cohen**[a]

[a] *CSIRO Data61, Clayton, Victoria, Australia*
Email: damien.watkins@data61.csiro.au

Abstract: The growing need for decision support, situational awareness and predictive analytics systems in real world iterative scenarios has given rise to the research field of "Digital Twins"; the combining of cyber-physical systems, artificial intelligence, computational processing platforms and mixed-reality visualisation. Digital Twins are living, digital replicas of a physical object, process or system and are comprised of three elements; a physical system; a digital model of that system; and the interactions that flow between these two systems.

In this paper we describe our approach to the ongoing task of building our Mixed Reality Lab (MRL) using our Scientific Workflow System (SWS) called Workspace and describe its characteristics that make it suitable for use in producing Digital Twins for both research and commercial applications. Digital Twins need to address many of the same issues that SWSs address, for example platform independence, handling large data sets, local and remote processing, algorithm integration, hardware integration, advanced visualisation, reproducibility and scalability. In general, we believe that the elements that make our SWS applicable to the creation of Digital Twins could also apply to other SWSs, subject to their capabilities in areas discussed in this paper.

Two prototypical use cases supported in our MRL, Defect Detection in Manufacturing scenarios and Human Movement (a.k.a. Digital Human) are outlined. Although these two use cases work at different scales, we see how both can be modelled in the MRL using the infrastructure constructed on top of Workspace.

Capability strengths of our SWS that are of particular importance to our Digital Twin use cases are discussed. These include: The use of both continuous execution (interactive) workflows with rich user interfaces as well as distributed, cross-platform, remote execution processing workflows; Advanced interactive visualisation capabilities ranging from 2D widgets and charts, OpenGL-based 3D rendering through to a real-time Virtual and Augmented Reality pipelines using third party rendering engines; a modular, extensible plugin based architecture that exposes capabilities from many permissive open source libraries combined with in-house developed capabilities; and a streamlined deployment and productisation process to support different distribution or commercialisation needs.

The MRL is very much a work in progress, optimisations to the current systems are ongoing and work to add extra facilities and infrastructure to support more scenarios is progressing.

Keywords: *Scientific Workflow Systems, Digital Twins, Mixed Reality*

Ergomechanic: A markerless motion capture and ergonomic assessment tool developed using the Workspace workflow engine

R. C. Z. Cohen and **S. M. Harrison**

CSIRO Data61, Clayton, Victoria, Australia
Email: Raymond.Cohen@csiro.au

Abstract: Motion capture of human activities is the process of generating a digital representation of the human body performing physical movements. It produces kinematic data, which are typically time series of body joint positions in either world or local body coordinate frames. Motion capture has applications to a range of industry sectors including biomechanics research, rehabilitation, ergonomics, film and sports. Traditional industry standard marker-based motion capture systems (e.g. Vicon Motion Capture System, Vicon, USA) have good spatio-temporal accuracy for detecting reflective markers placed on the body using infra-red cameras. However, this marker-based approach has a number of downsides including the high cost and space requirements of the systems; high time and expertise required to attached markers to each subject; and technical processes of post-processing marker positions to generate the kinematics data. These factors tend to limit both the volume of subjects and trials that can be considered, and the overall uptake of the technology across different sectors. Recently the fields of camera calibration, computer vision, and biomechanics have been combined to produce markerless motion capture (MMC), which can measure human movement without the need for placing any markers (or devices) on the body. When combined with biomechanical simulation, MMC can be used to calculate the number of repetitions of body movements, the speeds and accelerations of movement, and the resulting loading on the internal body structures.

Here we describe development of a prototype MMC software that was enabled by the use of computational workflows, specifically the Workspace workflow engine (Cleary et al., 2020). The software prototype, called Ergomechanic, is an MMC and ergonomic assessment tool (**Figure 1**). Code components from previous projects were immediately available for re-use due to the modular design of operations in Workspace. Interfacing with external libraries such as OpenCV was made robust and simple. Workspace's design facilitated an agile design process, during which the achievable ends were continuously evaluated and refined. Specifically, Workspace gives the designer the ability to: drag and drop or rearrange unit operations, interrogate any input or output of an operation in a suitable widget, use a well-featured OpenGL rendering engine, and a software packaging wizard for deployment. As a result, the current prototype has been developed in a relatively small amount of time and its underlying components can be easily redeployed for other software products with minor additional effort. Along with the software development, this paper highlights a case study of how to use the Ergomechanic platform to record human walking trials, process this data into detailed kinematic information and to objectively assess normal and pathological walking gaits.

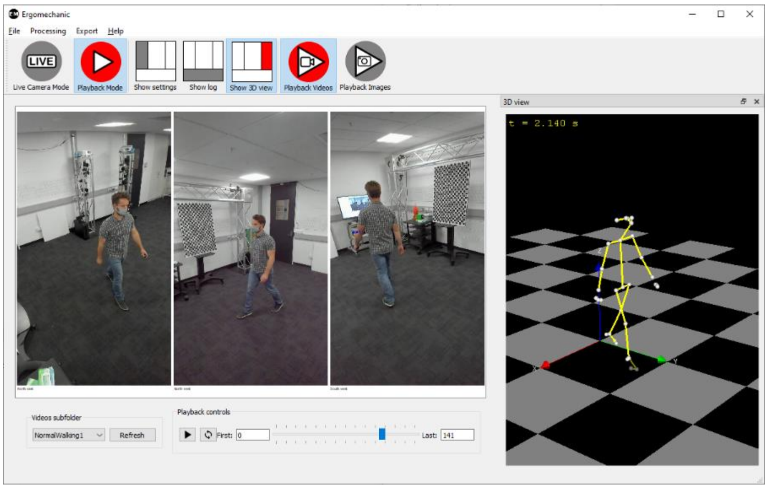

Figure 1. Ergomechanic software interface showing a normal walking trial

Keywords: *Workflow, software engineering, markerless motion capture, walking gaits, biomechanics*

Implementing a Fully Homomorphic Encrypted Circuit in Workspace

Dang Nguyen [a] **and Damien Watkins** [a]

[a] *Data61 CSIRO, Research Way, Clayton, VIC 3168, Australia*

Email: dang-quan.nguyen@data61.csiro.au

Abstract: Fully homomorphic encryption (FHE) schemes are regularly referred to as solutions for both privacy and security aspects in cloud computing. They allow a user's data to be encrypted in such a way that the cloud provider can still blindly manipulate the encrypted data on the user's behalf, i.e. by running some computations (called "circuit") on the encrypted data. Since its discovery a decade ago, FHE has become an active field of research with many encryption schemes proposed. When compared to non-FHE cryptographic functions, most of the FHE schemes require much larger memory space and longer execution time for their basic operations such as encrypt, decrypt and recrypt. This makes designing and experimenting with FHE circuits that have more than a few basic operations a very challenging task.

We present in this paper an implementation of Gentry's lattice-based FHE scheme as a plugin in Workspace. Workspace is a world-leading workflow software that allows to implement computational functions as operations then to reuse and rearrange them in a workflow to achieve larger and more complex functions. The operations' input and output data can be easily "wired" between the operations and Workspace automatically takes care of referencing the data, thus avoiding unnecessarily copying it between functions. The operations themselves are executed on a need-to-run basis, i.e. only when their outputs are required by some other executing operations and their inputs have been changed since their last execution. This can lead to a significant improvement in terms of both execution time and memory space required if the transitional data is large as in many FHE schemes. We experiment with this implementation in Workspace by creating a few basic circuits such as the obfuscated `if` ... `then` ... `else` ... statement and the $\texttt{MIN}(a, b)$ and $\texttt{MAX}(a, b)$ functions on encrypted data.

Keywords: *Workspace, workflow, homomorphic encryption, FHE*

Workspace Workflow Comparison

N. Oakes and D. Thomas

CSIRO Data61, Australia
Email: nerolie.oakes@data61.csiro.au

Abstract: Workspace is a Scientific Workflow System (SWS) that has been under development at the CSIRO since 2005. It is commonly used in a collaborative style with multiple people and or teams working on the same set of workflows. The workflows are serialized in XML format, and typically change periodically over time as the project develops. The main workflow development application is a graphical Workflow editor that helps the user to design and execute. Workspace also ships with Workflow comparison tool aimed at helping developers keep track of differences between multiple versions of the same workflow over time.

File comparison algorithms have a long history and are important components in fields as diverse as molecular biology, information processing, data retrieval and network security. There is always a trade-off between speed, breadth of application and development time. The Workspace workflow comparison tool is a highly customized XML comparison that parses two workflows, extracts semantically relevant information, compares the two sets of extracted information and produces an interactive graphical display that highlights relevant differences.

It presents differences in two different ways: a graphical display similar to the workspace editor with the extracted differences highlighted and a tree-based display that shows only the extracted differences.

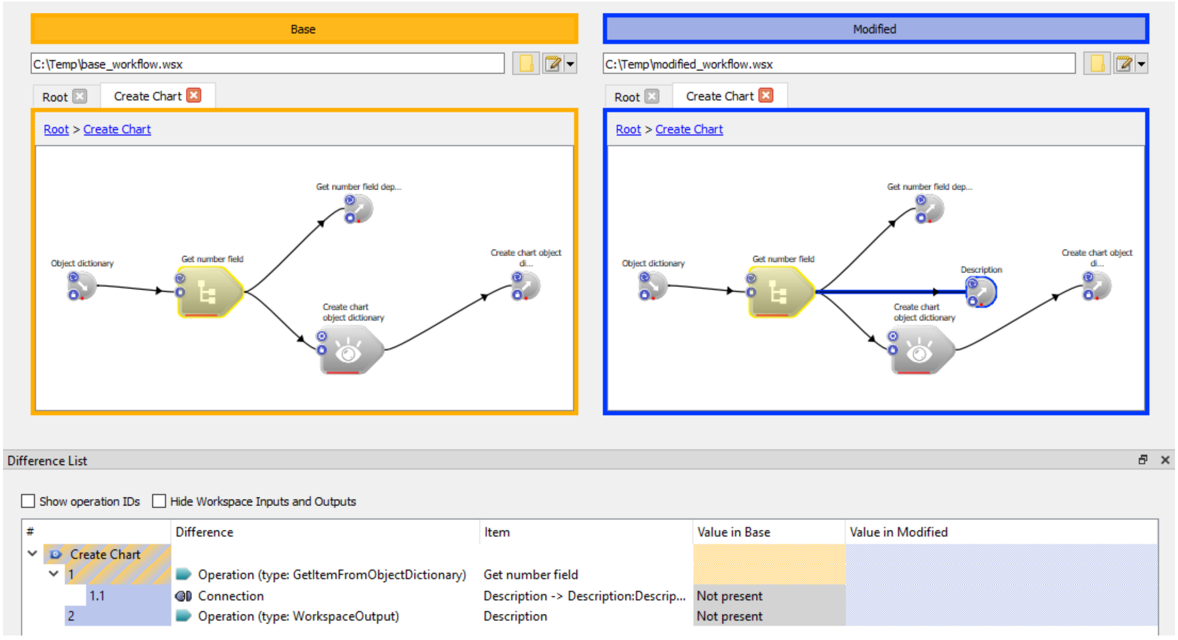

Figure 1. The Workspace Workflow Comparison Tool

In this paper, we discuss the types of workflow differences that are extracted, the difficulties of presenting this information using generic text-differencing applications, and how the workflow comparison tool helps overcome these. We also look a case study to study a set of workflows that were produced as part of a project stretching over eight years with workflow revisions saved to software versioning system.

Keywords: *Workspace, workflow, visualisation*

AeroDAQ: A Workspace based application

N. Sankaranarayanan[a] **and R. S. Humphries**[b]

[a]CSIRO Data61, Clayton VIC Australia and [b]CSIRO Climate Science Centre, O&A, Aspendale VIC Australia
Email: Nirupama.Sankaranarayanan@data61.csiro.au

Abstract: AeroDAQ is an original, stand-alone, Workspace-based software application developed by the CSIRO that provides a robust, open, flexible, and reliable data acquisition and visualisation system for Condensation Particle Counters (CPCs). These instruments are fundamental to air quality work and ongoing atmospheric composition measurements around the globe such as those aboard the highly publicised RV Investigator and Cape Grim Baseline Air Pollution Station.

The original software that comes with the instrument has several key limitations. The software is unable to run reliably for more than a few days and thereby requires regular manual restarting of the application. Additionally, data is saved in a proprietary binary format unable to be read outside the software environment provided by the vendor without export. Data visualisation in the software is also limited, restricting the ability to review data and performance in real-time. AeroDAQ was born of a desire to have a lightweight, portable, and reliable application that manages data acquisition from the instrument and data visualisation.

The Workspace scientific workflow and application development platform is well suited to the development of a stand-alone software application – AeroDAQ in this case. Workspace provides a versatile and extensible plugin architecture and has a close relationship to the Qt Toolkit. Workspace provided an easy interface for implementing both a serial port plugin for communication with the CPC and an application to capture and store received data. The vast suite of built-in operations allowed for quick creation of the complex workflows required to capture, process, and display data from the CPC. Third-party charting libraries like NVD3, VisJs and PlotLy are wrapped into Workspace and with the impressive range of built-in widgets, visualisation of data was made easy.

AeroDAQ represents the adoption of a new experimental standard in data acquisition and storage from CPC devices. It increases the productivity of the research scientists and technicians by providing them with the ability to visualise their data in real-time, allowing them to quickly identify and rectify instrument issues and experimentally respond to the scientific observations where appropriate. This reduces the research team's downtime, opens the data for presentation to others, increases confidence in the quality of the collected data, and enhances scientific output.

***Keywords**: Workspace, extensible architecture, visualisation*

Extending the capabilities of applications built using the Workspace architecture

R. Subramanian[a], **D.G. Thomas**[a] **and S. J. Cummins**[a]

[a] *CSIRO Data61, Clayton VIC Australia*
Email: Rajesh.Subramanian@data61.csiro.au

Abstract: Workspace (Cleary et. al (2020), Bolger et. al (2016), Cleary et. al (2013)) is a powerful, cross-platform scientific workflow framework that enables collaboration and software reuse. Workspace allows for the creation of custom operations that can be used in conjunction with a large set of powerful built-in operations to create scientific workflows. These custom operations can also be used in existing applications that are built with the Workspace architecture, enabling low-cost extension of the application capabilities without major reworking.

This paper describes the challenges a developer will face while producing a code that needs to be integrated into existing applications, and how the Workspace ecosystem can mitigate many of the obstacles in accomplishing this. This is illustrated with a case study, in which the following challenges are discussed:

1. Reusing the existing code that has already been built into an application.
2. Retrofitting the new algorithm code into existing applications.
3. Converting between the different data types that the old and new algorithms may work with.

Our specific problem:

We have a set of approximately twenty data processing utilities that allow analysis of specific types of simulation outputs, (see Cleary et. al (2020), Cohen et. al (2020) and Thomas et. al. (2019) for further details on these simulations). We would like to add general classes of additional analytical capability that can be deployed into these utilities (either into all of them, or on a user-need basis). Therefore, a flexible solution is required where code can be added or enabled across a broad range of similar utilities that have been developed by a range of different developers over several years.

In this specific case, we have developed a new Workspace operation that can perform smoothing of time-series data, and we would like to deploy this capability into some of the existing utilities.

The solution involved:

1. Adapting various kinds of data produced by the existing utilities to standardized types of data using the features available within the Workspace ecosystem.
2. Connecting the standardized data to the newly developed time-series smoothing operation and using it in lieu of the existing code.
3. Adding further plotting capabilities to assess the performance of the smoothing operation.

The existing applications and utilities that needed additional analytic capabilities were previously built on Workspace, which offered benefits in terms of re-use, extension, customization and commercial licensing. It is demonstrated that Workspace provides the flexibility and ease-of-use to allow the capabilities of a family of software applications to be effectively extended to make use of the new capability, which in this particular case are time-series smoothing algorithms. This is done without the need for any major rewriting or bespoke re-working of each software family member providing a large benefit for moderate cost.

Keywords: *Workspace, extensible architecture, plotting, scientific workflow software*

Sandwiches vs. genes. Sharing data to maximise its value.

Matthew Wysel[a] **and Derek Baker**[a]

[a] *The Centre for Agribusiness, UNE Business School, The University of New England, Armidale, Australia*
Email: mwysel2@une.edu.au

Abstract: When is it okay to give away data? Why do we feel comfortable sharing photos of sandwiches on social media, but hesitate to share genetic material with laboratories such as *23andme*?

We present a mathematical model of markets that trade in data, optimised under a variety of conditions. This micro-economy includes a data-producing asset-owner, an independent data analyst and a market that values both the owner's raw data and analyst's enriched data. The model proceeds as follows: suppose an agent desiring increased asset utilisation, generates data from assets it owns but cannot process the data itself. This data is shared with a for-profit analytics firm who both enriches the data for the owner and sells the enriched data as a separate digital product. The agent uses the analyst's services to increase asset utilisation but has lost control of their data. The agent's choice lies on a continuum: keep all data private and commercialise lower performing assets, through to cede all data and maximise the utility of their assets. We broaden the optimisation matrix to include data that decays at different rates – photos of sandwiches vs. genetic information – and repeated sharing across time intervals of different lengths.

We address the question: what private data should be shared to maximise value created from data?

We analyse the ecosystem (Fig. 1) and optimise for short-term owner profits (Fig. 2). Both functions are run over two time periods and driven by the proportion of data shared, σ ∈ [0,1]. The latter is also optimised against the terms that describe the owner and analyst's contract, δ ∈ [0,1].

The model is characterised using an existing, genetic micro-economy. An initial assessment of the real-world data sharing ecosystem is presented.

This paper connects the conditions surrounding data sharing with the payoffs each actor in the ecosystem can expect to receive and demonstrates sharing otherwise private data enables the creation of value from data.

Application includes conditions regarding when to trade data and how to create value from privately held data. The conclusions inform design of data contracts and management of data access.

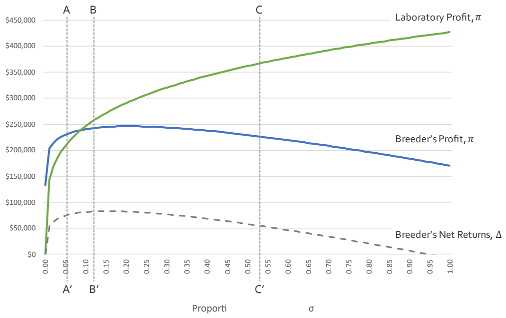

Figure 1. Profit across data sharing ecosystem for $\sigma \in [0,1]$

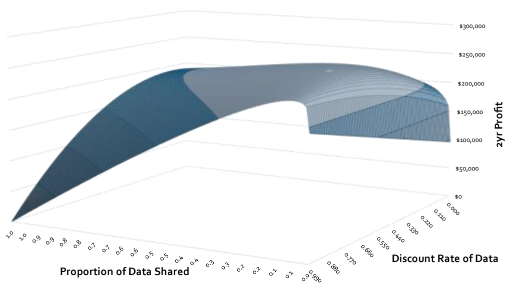

Figure 2. 2-stage optimisation of owner profit for $\sigma \in [0,1]$ and $\delta \in [0,1]$

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Keywords: *Datanomics, value of data, data sharing platforms, multi-dimensional optimisation*

Environmental Information Modelling: bringing sustainable development into the digital age

L. Bruce[a,b] **and Philip Kindleysides**[a]

[a] *BMT Commercial Australia, Brisbane, AUSTRALIA.*
[b] *The University of Western Australia, Perth, AUSTRALIA.*
Email: louise.bruce@bmtglobal.com

Abstract: The United Nations Sustainable Development Goals adopted by Member States in 2015 set an ambitious global initiative to improve human lives through economic growth while protecting the natural environment for future generations. Two processes underpinning sustainable development are the Environmental Impact Assessment (EIA) in the planning stage and the development of an Adaptive Management Plan (AMP) for the project construction, operation and decommissioning stages of development. In this study we introduce the concept of Environmental Information Modelling (EIM) as building a virtual representation or "digital twin" of the environment. The EIM approach supports the application of information technology to sustainable development goals as an adaptive management tool that recognises the need for continuous improvement in response to new challenges in a changing world. EIMs combine tools for data sourcing, analytics, management, communication, and visualisation in a single point of truth to enable collaboration between stakeholders, regulators, and industry.

Rapid growth of information technology on a global scale is transforming environmental management by enabling greater access to and communication of data, knowledge and information (World Bank 2016), leading to informed decision making. The notion of EIMs is not new, the concept of a Digital EIA (Farber 2006), building an Environmental Virtual Observatory (Emmett et al. 2014) and the development of the FAIR Guiding Principles (Wilkinson et al. 2016) all seek to move environmental management into the digital age by promoting a collaborative digital infrastructure for use in environmental management for sustainable development. The basic principles underling EIMs are smart data sourcing, clever data management, intelligent storage, and meaningful and accurate communication all leading to reduced efforts on the behalf of engineers, scientists. and decision makers to make informed decisions when and where they are needed.

One of the main advantages of building an EIM in support the development of a Digital EIA is that the data, information, knowledge, analytics, workflows, visualisation, data sharing platform, and digital infrastructure developed in the planning stage can be readily transferred for use as an AMP tool to support sustainable operations post construction (Figure 1). Another advantage of developing EIMs over traditional AMPs is the ability to connect ecosystem models and monitoring data with changes in policy, communication and feedback from key stakeholders, and community science data. In this way the evaluation and learning steps are enhanced and management plans can adapt in response to directives from all four principles of sustainable development, economic, environmental, societal, and cultural.

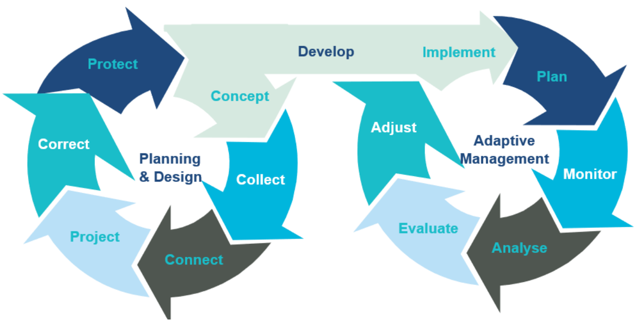

Figure 1. Environmental Information Models from planning and design stage to use in adaptive management.

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Keywords: *Environmental Information Model, Digital EIA, sustainable development*

A customizable process-based strategy for collaborative geographic analysis

Zaiyang Ma[a,b,c], Min Chen[a,b,c,*] Songshan Yue[a,b,c], Zhiyi Zhu[a,b,c] and Yongning Wen[a,b,c]

[a] *Key Laboratory of Virtual Geographic Environment (Ministry of Education of PRC), Nanjing Normal University, Nanjing, Jiangsu, China.*
[b] *Jiangsu Center for Collaborative Innovation in Geographical Information Resource Development and Application, Nanjing Normal University, Nanjing, Jiangsu, China.*
[c] *State Key Laboratory Cultivation Base of Geographical Environment Evolution (Jiangsu Province), Nanjing Normal University, Nanjing, Jiangsu, China.*

Email: mzaiyang@outlook.com (Zaiyang Ma); chenmin0902@163.com (Min Chen, Corresponding author)

Abstract: Geographic analysis can be utilized to assist in addressing various geographic problems using different means, including data analysis, model construction, geographic simulation, and decision making (Revolution, 1999; Lü, 2011). Due to the advantage in idea sharing, data reuse, and joint analysis, collaborative geographic analysis is required and can lead to better outcomes (Voinov et al., 2016; Usón et al., 2016; Chen et al., 2020).

Since the process of collaborative geographic analysis is usually complicated and involves many iterative attempts, which creates some obstacles to problem-solving. To improve collaborative geographic analysis, the process should be clarified and customized. Therefore, many studies have attempted to provide indicative processes to support geographic analysis (Scolobig et al., 2016; Cradock-Henry et al., 2020); however, difficulties remain in adaptive process customization and further process-based process implementation.

In this article, we propose a customizable process-based strategy for collaborative geographic analysis. This method includes the customization of the collaborative geographic analysis process and a support strategy for process-based geographic analysis implementation. The process customization is based on a hierarchical description model and a protocol-based activity linking method, which can help participants to collaboratively customize and optimize the hierarchical geographic analysis process. The support strategy can provide a collaborative environment that can help participants access geographic analysis resources and tools during the collaboration process. Thus, the entire process of collaborative geographic analysis can be implemented to address geographic problems.

To verify the feasibility and capability, the method was implemented in a prototype system developed for collaborative geographic analysis, and a case study on traffic noise assessment was considered. The results suggest that the proposed method can improve geographic analysis by customizing and optimizing processes, guiding participants, performing collaborative geographic analysis, and recording operations throughout the process.

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Keywords: *Geographic analysis, collaboration, process customization, urban traffic noise assessment, OpenGMS*

Algorithms for diffusion and convection models implemented using open source libraries

E. Mas-Hernández [a] [b], **E. A. Mancilla-Barría** [a], **M. de la Torre-Sanzana** [a] **and S. Berres** [b]

[a]*Faculty of Engineering, Catholic University of Temuco, Rudecindo Ortega 2950, Temuco, Chile, 4813302*
[b]*Bioproducts and Advanced Materials Research Nucleus (BioMA), Catholic University of Temuco, Rudecindo Ortega 2950, Temuco, Chile, 4813302*
Email: elimher@gmail.com

Abstract: There are several phenomena where the description by mathematical models is in terms of differential equations. Among these phenomena, we can find (1) the diffusion of pollution particles, (2) the growth of metal nanoparticles, and (3) the displacement of foam within porous media. In this paper we present some solutions for models that depict the two first processes of interest mentioned above, which were programmed using libraries for Python™, and explore the possibility of applying the programming framework to the third application.

The diffusion of air pollutants, specially particulate matter, can be modelled with an advection-diffusion equation. This equation makes it possible to consider the phenomena that describe the change in concentration of particulate matter (PM_{10} and $PM_{2.5}$) with time and also the effects of wind and rain. The chosen method to tackle the solution for the advection-diffusion equation is the finite-volume method, and its respective algorithm makes use of a triangular grid.

On the other hand, the growth of copper nanoparticles on silicon surfaces can be approached from different perspectives. Until now we have explored curve fitting to obtain equations that approximate experimental data. In addition, the Hamilton-Jacobi equation has been also used to describe this process. Both, curve fitting and the solution of Hamilton-Jacobi equation have been implemented in Python.

Finally, the flow of a foam front inside a porous medium can be described using a simplified model for bubble films known as the pressure-driven growth model. In this application, different formulations can be used as well. In particular, an Eulerian model can make use of the so-called Eikonal equation to address its solution using triangular meshes.

Implementations of the algorithms to solve the models for the applications of interest use libraries for Python, mainly NumPy, OpenMesh©, Matplotlib, pandas, and scikit-image.

Keywords: *Open software, differential equations, contaminants diffusion, copper nanoparticles, foams*

Effects of ground-level ozone pollution on yield losses of winter wheat in the North China Plain

Tuanhui Wang[a, c†] and Hongquan Song[a, b*†]

[a] Laboratory of Geospatial Technology for the Middle and Lower Yellow River Regions, Ministry of Education, Henan University, Kaifeng, Henan 475004, China
[b] Henan Key Laboratory of Integrated Air Pollution Control and Ecological Security, Henan University, Kaifeng, Henan 475004, China
[c] Institute of Urban Big Data, College of Geography and Environmental Science, Kaifeng, Henan 475004, China
E-mail: hqsong@henu.edu.cn (Hongquan Song)

Abstract: Ground-level ozone (O_3) has strong oxidation, which produced of precursors such as nitrogen oxides (NOx) and volatile organic compounds (VOCs) under the photochemistry (Guo et al., 2019; Wang et al., 2019), and also has significant negative effects on ecosystems, human health, and climate change (Cooper et al., 2014; Zhao et al., 2018; Agathokleous et al., 2020; Zhao et al., 2020).

Some studies had shown that the North China Plain (NCP) was one of the serious ozone pollution regions in China (Feng et al., 2020; Hu et al., 2020). The NCP is one of the important grain producing areas in China. The winter wheat and maize yield account for about 60% and 24% of its total yield, respectively (Feng et al., 2020; Hu et al., 2020).

In this article, the AOT40 (accumulation of hourly O_3 concentrations exceed 0.04 ppm) and POD_{12} (Phytotoxic Ozone Dose over a threshold of 12 nmol m^{-2} s^{-1}) indexes were calculated using hourly meteorological data and ozone concentration provided by the Weather Research and Forecasting model coupled with Chemistry (WRF-Chem) in this study. The yield and economic losses of winter wheat caused by the ground-level ozone pollution were assessed by AOT40 and POD_{12} indexes from 2015 to 2018 in the NCP. The O_3, AOT40, and POD_{12} in the NCP was growing during 2015-2018, respectively, with the mean values of 0.044 ppm, 5.32 ppm h and 1.78 mmol m^{-2}, respectively. The AOT40, POD_{12}, and relative yield losses of winter wheat (WRYL) had the significant spatial and temporal variations in NCP during the study period. The WRYL in the NCP assessed by AOT40 and POD_{12} was 10.9% and 14.6%, respectively, and associated with 1022.72 × 10^4 and 1465.08 × 10^4 metric tons, respectively.

The study found that the sensitivity of winter wheat to POD_{12} was higher than the AOT40 index, which indicated that the local climate changes affect the response of winter wheat to ground-level ozone concentrations. The development of ozone pollution response function to crops for different regions was needed to improve the assessment results in the future.

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Keywords: *WRF-Chem, POD_{12}, AOT40, winter wheat, food security*

Study on sharing and reusing geographic simulation models in web environment

Kai Xu [a,b,c], **Min Chen** [a,b,c], **Songshan Yue** [a,b,c], **Yongning Wen** [a,b,c], **Guolian Lu** [a,b,c], **Fengyuan Zhang** [a,b,c] **and Jin Wang** [a,b,c]

[a] *School of Geography, Nanjing Normal University, Nanjing, 210023, China*
[b] *Key Laboratory of Virtual Geographic Environment (Nanjing Normal University), Ministry of Education, Nanjing, 210023, China*
[c] *Jiangsu Center for Collaborative Innovation in Geographical Information Resource Development and Application, Nanjing, 210023, China*
Email: xukai1215@126.com

Abstract: Modelling is an effective method to simulate geographic phenomena and processes and solve geographic problems. To date, many experts and scholars have constructed massive geographic analysis models to meet the requirement for simulation of different geographical scenarios. For complex geographic problem solving, collaborative modelling and integration is becoming more popular. As a key factor for collection, how to share models become a new trend in geographic research. Due to the heterogeneous of models, diverse models have different methods of description, different structures and different using processes, it's hard to recognize, share and reuse models in a common way. In order to reduce the difficulty of sharing models, related research achieve model sharing and reusing in different levels and kinds of requirement, such as model knowledge acquiring, model building and model using. For example, Maxwell and Costanza designed a modular modeling language (MML) (Maxwell and Costanza, 1997) to describe the cognitive problems of models. The CSDMS platform uses standardized names to describe the input and output of the model (Overeem et al., 2013). For the sharing of models, Gehlot et al. (2006) proposed the sharing of geographical processing chain based on network. HydroShare platform is based on Open Archive Initiative's Object Reuse and Exchange (ORI-ORE) standards to share model resources (Lagoze et al., 2007; Horsburgh et al., 2016). However, a single function is difficult to meet the needs of the composite role, and complex application scenarios still restrict the sharing of models. This paper summarizes the process of models' building and using, and divides it into four parts: model item, conceptual model, logical model and computable model, which can give a structural description of basic information, mechanisms, structures and running processes of models, and satisfy different users' requirement for model recognizing, model building and model invoking. Finally, we present a web system to show different levels of model achievement would benefit models' sharing and reusing, in which people can recognize and invoke models as web services.

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Keywords: *Geographic simulation models, sharing, reusing, web service*

An action-based conceptual framework for the reproduction of geographic simulation processes

Zhiyi Zhu[a,b,c], **Min Chen**[a,b,c,*], **Songshan Yue**[a,b,c], **Zaiyang Ma**[,b,c], **Yongning Wen**[a,b,c]

[a] *Key Laboratory of Virtual Geographic Environment (Ministry of Education of PRC), Nanjing Normal University, Nanjing, Jiangsu, China.*
[b] *Jiangsu Center for Collaborative Innovation in Geographical Information Resource Development and Application, Nanjing Normal University, Nanjing, Jiangsu, China.*
[c] *State Key Laboratory Cultivation Base of Geographical Environment Evolution (Jiangsu Province), Nanjing Normal University, Nanjing, Jiangsu, China.*
Email: zhuzhiyi1030@163.com (Zhiyi Zhu); chenmin0902@163.com (Min Chen, Corresponding author)

Abstract: Reproducibility is important to prove the credibility and reliability of scientific researches and thus for geographic research as well (Goodman et al., 2016; Gil et al., 2016; Nüst and Pebesma, 2021). Currently, the reproduction of a geographic problem-solving mainly focuses on data availability, code executability and documentation accessibility(Gil et al., 2016; Konkol et al., 2019). These efforts provide peer scholars an easier way to acquire related resources and improve the repeatability of results. However, confronted with the comprehensiveness and complexity of a geographic problem, it is still difficult to ensure reproducibility by just focusing on the sharing and operation of resources.

A geographic problem-solving is usually a collection of complicated geographic simulation processes including problem definition, plan formulation, simulation execution and results analysis. It is obvious that the reproduction of a geographic problem-solving needs to support these processes constructed by research contributors. Moreover, peer scholars can be directed to understand the purpose of a problem-solving, verify the feasibility of execution and reproduce the results based on these processes. Nevertheless, there are still some challenges that peer scholars have a holistic recognition of a geographic problem-solving through reproduction need to be overcome.

Therefore, this article proposes an action-based conceptual framework for the reproduction of geographic simulation processes. A set of actions are designed to describe and represent geographic simulation processes via supported online components. Meanwhile, these actions are summarized as problem description, resource collection, simulation construction, result comparison and analysis. When research contributors reproduce processes of geographic problem-solving under this framework, solutions to solve this problem can be easily structured and interpreted, while peer scholars are also convenient to understand pre-and intermediate procedures step by step. Based on these actions, this article applies an example implementation for a simulation case, diurnal cycles of precipitation over China, to demonstrate how this framework can trace and reproduce how the resolution plan made and how the work implemented steadily by researchers when solving a geographic problem.

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Keywords: *Reproduction, geographic simulation processes, geographic problem-solving*

Towards a provenance-enabled, reproducible, and extensible machine learning platform by integrating databases, web services, containers, and code repositories in a loosely coupled manner

R.M. Singh [a], **P. Wilson** [b], **L. Gregory** [b], **S. Seaton** [a] **and B. Malone** [b]

[a] *CSIRO Land & Water, Canberra, ACT*
[b] *CSIRO Agriculture & Food, Canberra, ACT*
Email: *ramneek.singh@csiro.au*

Abstract: To create a provenance-enabled, extensible machine learning (ML) platform is an exercise that can involve different pieces of software: databases which supply the data to create the model and can also potentially store the result of predictions, web services that allow for ingestion of data into databases and also supply data out of the database to the consumer, code repositories that can be used to track the versioning of models for the sake of provenance and last but not the least the machine learning models themselves. Here we present an approach that we used to create a Soil Spectral inference platform by integrating these software components along with the use of Docker to create a technology agnostic, loosely coupled ML platform. The approach we show here demonstrates how metadata stored in a database can be used not only to drive a workflow but also that a database driven approach allows for extension points where new logic can be plugged-in to expand the capability of the platform.

In our approach, the database plays the central role in the application design. It faithfully reflects the entities involved in problem space. Instead of starting off with a more agile approach of creating, or prototyping, applications to reflect the ML workflow, we invested some time beforehand, understanding the domain to tease out the domain objects, their relationships to one other and the likely workflows that the ML platform will support. We also involved potential future external users in key discussions to understand their workflows and make sure our database is flexible enough to accommodate their concepts. In all this, we used the database schema diagram as a key artifact to consolidate the understanding of the domain, to make explicit the relationships between more prominent entities and to communicate with different team members on the project. Once the schema was in a stable enough state that we started designing the applications that would run off it.

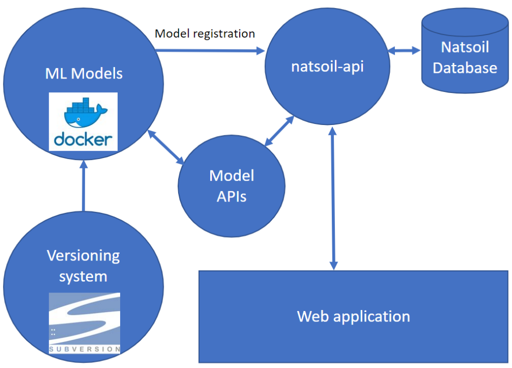


Figure 1. Architecture of the ML platform running off a database.

The ML platform applications use the metadata about extensions point stored in the database to implement the machine learning workflow. At the project onset it was decided to use a tech stack that was portable and for those components where we could not control the technologies being used, such as the ML models themselves, we used Docker containers to abstract away the implementation details and expose the model to the platform as a set of interfaces that would remain common for all the models hosted on the platform.

For provenance, we decided to use Subversion, which is an open-source version control system and can handle large files. The ML models and the input data that was used to build the models is versioned in subversion, and that version information is used as ML model metadata in the database to track provenance.

The loosely coupled framework template that we used is modular in nature and the subsystems are connected to each other through web service end points. It can handle future changes by combining, modifying or adding more subsystems visible through the database, each exposing its capabilities through web services.

Keywords: *Machine learning models, databases, web services, model provenance, docker containers*

An interaction of computer and human intelligence in agent based modelling

Firouzeh Taghikhah [a], **Alexey Voinov** [b], **Tatiana Filatova** [c] **and J. Gareth Polhill** [d]

[a] *Crawford school of public policy, Australian National University, Australia*
[b] *University of Twente, the Netherlands*
[c] *Delft University of Technology, The Netherlands*
[d] *Information and Computational Sciences, The James Hutton Institute, Aberdeen, Scotland, United Kingdom*
Email: Firouzeh.th@gmail.com

Abstract: When it comes to applying agent-based modeling (ABM) in practice, defining behavioral rules to reflect the heterogeneity of the agents' decision-making process is one of the main challenges. Even when detailed data about a particular matter is available, the modeler requires proper knowledge of simulation modeling techniques and the simulated systems themselves to derive the agent's rules and find the feedback loops. Moreover, when developing an ABM, they need to conduct extensive calibration tests, which are time-consuming and sometimes complicated. We propose a combined machine learning (ML) and ABM (ML-ABM approach) to facilitate the model development by integrating ML algorithms with behavior change theories to address these technical challenges. We show the feasibility and application of this approach in a case study focusing on organic food purchasing behavior. Integrating explainable artificial intelligence then, we build the causal relationships, identify feedback loops, and derive predictive functions for the explanatory factors of behavior. The comparison of ORVin-ML and its empirical counterpart (ORVin-E) reveals that the machine-driven approach can capture the uncertainty of agents' behavior due to bounded rationality and mimic their actual choices with comparatively high accuracy. We conclude that our suggested approach can speed up the modeling process without compromising the quality of outputs. In the simulation modeling field, AI can open up a new stream in modeling practices and provide opportunities and insights for future applications.

Keywords: *Behavioural rules, machine learning, explainable AI, agent based modeling*

Pump pressure tracking control of high-pressure pumping irrigation systems

Ye Wang [a], Qi Zhao [b], Erik Weyer [a], Wenyan Wu [b,c], Angus Simpson [c,b] and Ailsa Willis [d]

[a] *Department of Electrical and Electronic Engineering, The University of Melbourne, VIC 3010, Australia*
[b] *Department of Infrastructure Engineering, The University of Melbourne, VIC 3010, Australia*
[c] *School of Civil, Environmental & Mining Engineering, University of Adelaide, SA 5005, Australia*
[d] *Lower Murray Water, Mildura, VIC, Australia*
Email: ye.wang1@unimelb.edu.au

Abstract: Pressurised irrigation water networks supply water to irrigation and residential users through pipes. The increase in water demand has led to increased pumping and correspondingly larger energy costs, as well as increased greenhouse gas (GHG) emissions. The water sector in Victoria, Australia has committed to reducing its emissions by 42% by 2025 and to net-zero emissions by 2050, under Victoria's water plan, Water for Victoria (Department of Environment Land Water and Planning, 2018). For Lower Murray Water (LMW), this objective translates into a total reduction of 15,535 tonnes of GHG emissions by 2025.

Within the LMW's four irrigation systems, the Robinvale High-Pressure System (RVHPS) has a very high energy cost and associated GHG emissions (due to souring of fossil fuel-based energy sources), contributing to approximately 60% of the water utilities' total electricity cost. Currently, the pump station of the RVHPS is operated using a proportional-integral (PI) controller with a pressure setpoint found from a flow-setpoint curve. The flow is the aggregated current demand usage by irrigation users. Depending on the demand and the location of the currently operated irrigation outlets at times this curve may give a setpoint that is unnecessarily high, leading to unnecessary extra energy costs; while at other times the setpoint may be too low, leading to pressures below the service requirement at some irrigation outlets.

In this study, we propose a new strategy to find pump pressure setpoints. The strategy takes advantage of the flow measurement information from all the irrigation outlets to identify the most critical irrigation outlet in terms of the downstream minimum required pressure. Then, a new pump pressure setpoint can be determined based on this critical outlet. This leads to pumping energy cost savings, GHG emission reductions and an improved level of service to irrigators.

We have simulated the RVHPS with the new strategy for determining pump pressure setpoints. The economic and environmental benefits that can be achieved using the new control strategy for selecting setpoints are demonstrated across two days during the peak season in 2019 (i.e., from 28th and 29th of December 2019). A comparison between the new pump setpoints and the existing setpoints has been carried out. The current setpoints are for most of the time higher than the setpoints produced by the proposed strategy. The average reduction in setpoint values is approximately 4.50 m. This shows that the new strategy can lead to lower pump energy consumption and lower associated GHG emissions while delivering the minimum service pressure head downstream to all the active irrigation outlets. During the two days investigated in this study, 4.74% savings in both energy consumption/cost and GHG emissions were achieved. In absolute terms, over the two days, this corresponds to 7.08 MWh in pumping energy, $600 in pumping energy cost, and a reduction of 7.72 tonnes in GHG emissions.

Keywords: *Pump pressure setpoints, energy cost savings, greenhouse gas reduction, level of service, high-pressure irrigation systems*

Optimal design of water distribution systems incorporating behind-the-meter solar energy

Q. Zhao [a], W. Wu [a, b], A. R. Simpson [b, a] and A. Willis [c]

[a] *Department of Infrastructure Engineering, The University of Melbourne, Victoria 3010, Australia* [b] *School of Civil, Environmental and Mining Engineering, The University of Adelaide, South Australia 5005, Australia,* [c] *Lower Murray Water, Victoria 3500, Australia*
Email: jason.zhao1@unimelb.edu.au

Abstract: Water distribution systems (WDSs) are an essential part of rural and urban infrastructure systems. In order to meet the ever-increasing energy demands for distributing water, and to mitigate environmental impacts and obtain economic benefits, water utilities are beginning to consider on-site renewable energy generation and storage facilities. These are commonly referred to as behind-the-meter (BTM) energy systems. There has been previously a lot of research effort on optimising the design of WDSs. Most of these studies have either ignored BTM energy sources or incorporated BTM energy options in an ad-hoc fashion on a case-by-case basis. Therefore, the aim of this study is to develop an integrated approach for optimising the design of WDSs that consider BTM solar energy options.

In this study, a multi-objective optimisation (MOO) problem has been formulated for the optimal design of a real-world WDS considering BTM solar energy. The objectives considered include the minimisation of the total life cycle cost and total life cycle greenhouse (GHG) emissions over the system design life. Pipe diameters and solar PV sizes are regarded as decision variables. A new pipe classification method considering ground elevations and energy losses upstream of a certain pipe has been developed to reduce the number of decision variables for complex WDSs with a large number of pipes. The minimum allowable pressure is set as the inequality constraint in the optimisation. A multi-objective Genetic Algorithm (i.e. the NSGA-II) has been selected for optimising both the economic and environmental objectives. Present Value Analysis (PVA) has been used to calculate the total life cycle cost and total life cycle GHG emissions, with the selection of appropriate discount rates.

The case study system is the Robinvale High Pressure System (RVHPS), which is located in the Robinvale Irrigation District, Victoria, Australia and part of the Lower Murray Water utility's supply area. Raw water is pumped from the Murray River and delivered to customers for both irrigation and domestic & stock (D&S) water use. Different flow limits are required for each irrigation outlet. All irrigators need to order water in advance and take turns to irrigate, in order to satisfy the crop needs and maximise the use of the system capacity.

The results indicate that trade-offs between the total life cycle costs and total life cycle GHG emissions exist over the design life of the WDS. As shown in Figure 1, the reduction of total life cycle GHG emissions can increase the total life cycle cost and vice versa. Specifically, when the GHG emissions are high, a relatively small increase in cost is required to significantly decrease GHG emissions. For example, moving from solution A to B costs only $45 per tonne of carbon dioxide equivalent (CO2¬-e) reduction. Also, increasing the initial capital investment for installing larger pipes and solar panels can significantly save ongoing operational costs and associated GHG emissions.

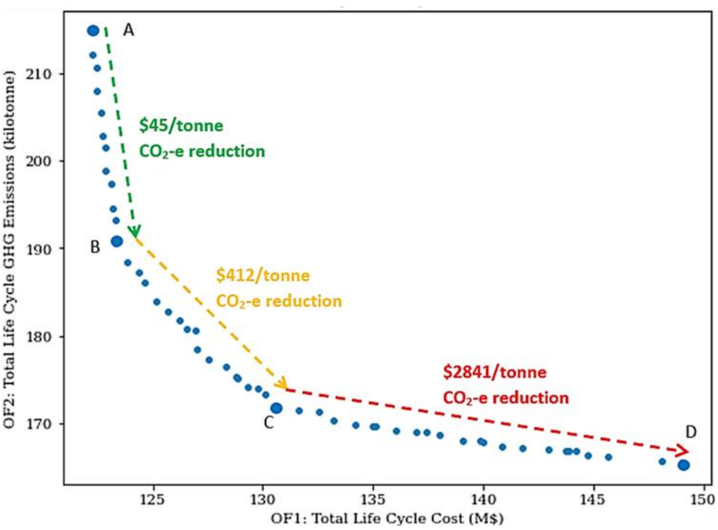


Figure 1. Optimal solutions obtained along the Pareto front

Keywords: *Water distribution system design, pipe sizing, behind-the-meter energy, solar PV, optimisation*

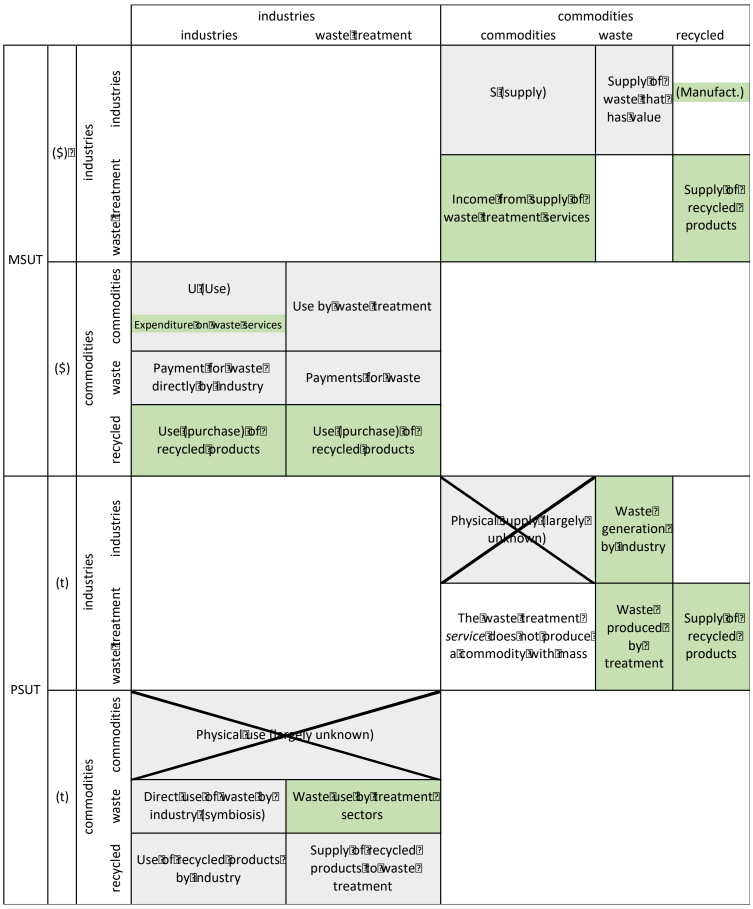
A Waste and Recycling Input-Output Framework for concurrent monetary and physical flows accounting

T.M. Baynes [a] and **J. Fry** [b]

[a] *CSIRO Land and Water, Level 5, 13 Garden St, Eveleigh 2015, New South Wales, Australia*
[b] *Integrated Sustainability Analysis (ISA), School of Physics, University of Sydney, Australia*
Email: tim.baynes@csiro.au

Abstract: Waste and recycling, and related circular economy initiatives, have come into prominence with the cessation of internationally traded waste flows[1]. Australia's limited recycling capacity and reliance on landfill are major challenges leading to issues like stockpiling of recyclable material. These same challenges are faced globally, as addressed in UN Sustainable Development Goal (SDG) 12.

To monitor national progress, it is important to measure waste and recycled resource flows and corresponding monetary transactions. Data on waste collected and treated is available[1], and the ABS experimental waste accounts[2] record the macro-economic 'supply' of "*Waste Collection, Treatable and Disposal Services*" (IOPC 2901) and 'use' of waste as physical inputs to that same service. For a more complete account of material and value flows in a circular economy, it is also important to know how much recycled material is stockpiled, or returned to the economy after recycling, and in which sectors. This is a data gap we resolve with a Waste Input-Output Framework (WIOF). The WIOF is constructed from a monetary supply-use table (MSUT) with a linked physical supply-use table (PSUT). The WIOF has an accounting structure that particularly identifies waste treatment sectors, waste flows and recycled material flows using ABS publications, industry reports, the Australian System of National Accounts, and the National Waste Database[1].



To estimate national stockpiles, we define a vector $\boldsymbol{p}_k$, the maximum degree of substitution between virgin commodities and waste type k. With zero stockpiling, all recyclable flows would be consumed either in the domestic demand of industry or in exports, ($\boldsymbol{p}_k$ = 100%). This is not the case and so we expect $\boldsymbol{p}_k \leq 100\%$. In estimating this for k = 31 materials, we interrogate the engineering literature, apply dis-aggregation (downscaling) and estimation techniques to infer detailed or unknown quantities. These estimations do not disturb the IO table balance or change the magnitude of industry output in the economy, but they permit an accounting of physical recycled return flows to the economy concurrent with their monetary counterparts.

[1] https://www.environment.gov.au/protection/waste/publications/national-waste-reports
[2] https://www.abs.gov.au/statistics/environment/environmental-management/waste-account-australia-experimental-estimates

Keywords: *Circular economy, input-output, material flow accounting, PIOT*

Modelling the circularity of pastoral sheep and beef farms

V.T. Burggraaf and **G.J.K. Mercer**

[a] *AgResearch Ltd, Ruakura Research Centre, Private Bag 3123, Hamilton 3200, New Zealand*
Email: vicki.burggraaf@agresearch.co.nz

Abstract: The increasing global population has led to concerns over the limited resources to grow food, the waste in the food system and the environmental impact of food production. As a result, food production systems are looking to become part of a circular economy, where nutrients are used efficiently and recycled in the food system, and nutrient losses are minimised. If agriculture is to optimise circularity, benchmarking tools and models are required.

We developed a methodology to assess nutrient circularity in pastoral farming systems, based on the flow of nitrogen (N), phosphorus (P) and potassium (K) into and out of a farm, and the degree of circularity of these flows. This was applied to 17 New Zealand sheep and beef farm typologies, representing 8 farm classes across five regions of New Zealand that varied from intensive finishing farms with mixed cropping, to extensive high-country farms. Farm typologies, based on industry data, were modelled over one year (2015). Nutrient budgets were prepared using OVERSEER®Sci version 6.3.4 (*Overseer*; https://www.overseer.org.nz), with outputs reported in kg/ha/year. Each model farm comprised management blocks based on topography and crop or pasture type, with site specific soil types and climate. Monthly livestock numbers and fertiliser application use were inputs into the model. The nutrient flows into animal product, soil pools, and losses from the root zone or into the atmosphere were then modelled.

To determine the circularity of these nutrients, the Material Circularity Indicator (MCI; https://www.ellenmacarthurfoundation.org/resources/apply/material-circularity-indicator) was estimated by applying in turn N, P and K flows from *Overseer* for each farm to the equation:

$$MCI = 1 - (V + W) / 2M$$

Here, W is waste (including dumped materials and nutrient losses to the atmosphere or below the root zone) and M is the total mass of inputs, including virgin (V) and sustainable (S) inputs. Biologically fixed nitrogen, nutrients from rainfall and purchased animals were classified as S, and mineral fertiliser as V.

Potassium fertiliser was not included in any of the systems modelled. As stocking rate increased across the farming systems, nitrogen and phosphate fertiliser use also increased, as did N losses. An exception was the farm which consisted of more than 50% cropping, where W was high relative to stocking rate. On that farm, N fertiliser inputs were more than triple that of the farm with the next highest fertiliser input, but nutrient losses were less than double. There was no relationship between stocking rate and P or K losses.

Nitrogen circularity ranged from 0.5 for the intensive mixed livestock finishing and cropping farm, to 0.8 for both low intensity high country farms, which had minimal fertiliser use or nutrient losses. Phosphorus and potassium circularity ranged from 0.4 to 0.6 and -1.4 to 0.4, respectively across farms. For these nutrients, circularity was highest for the mixed livestock finishing and cropping farm, as a large proportion of the total P and K inputs were from purchased animals (classed as sustainable inputs), as opposed to fertiliser, and the proportion of total inputs ending up as waste was also low.

Applying the MCI to livestock farms was complex. The MCI is between 0 and 1 for manufacturing industries, but we found potential for a negative MCI, when calculated nutrients lost from soil were greater than total inputs in a given year. Also, the equation only accounts for total inputs and waste, assuming all non-waste material ends up in product. In agricultural systems some of the inputs may be stored on farm via conserved feed or a gain in animal liveweight or soil nutrients, which could end up as either product or waste in later years. Once these inconsistencies are addressed, there is potential for this methodology to be applied to multiple farming systems to assess circularity, including a range of desired nutrients.

Keywords: *Circular economy, material circularity indicator, nutrients, OVERSEER*

Regional assessment of the circular economy: Data gaps

Kyle Stevens[a] and Will Rifkin[b]

[a]*School of Information and Physical Sciences, University of Newcastle, NSW, Australia 2308*
[b]*College of Human and Social Futures, University of Newcastle, NSW Australia 2308*
Email: kyle.stevens@uon.edu.au

Abstract: The circular economy presents an opportunity to employ modelling expertise to identify how best to keep materials in use at their highest value and to enable regeneration of the natural environment. However, analysis for a consultancy project for the Hunter and Central Coast of New South Wales indicates that data gaps at the regional level in Australia must be addressed first to whet the appetites of local governments for more sophisticated assessment.

Circular economy strategies adopted by industry promise to help limit greenhouse gas emissions, with production and use of materials credited with 45% of total emissions (Ellen MacArthur Foundation, 2020). Analysis to inform initiatives to bolster the circular economy has focused at the national level and on major cities in Europe and Asia (see the meta-analysis of Aguilar-Hernandez, et al., 2021). Analyses in Australia have been emerging in recent years (*e.g.*, KPMG Economics, 2021; PwC, 2021; Lifecycles, 2017).

Australia's regions face unique challenges in relation to circular economy opportunities compared to the capital cities. A relatively low population density can make distance a hurdle because transport can add a significant percentage to the cost of low-value materials headed for recycling. Additionally, a local government area with 50,000 residents could struggle with mattress recycling, whereas a region with 500,000 residents could yield a viable 200 used mattresses per day. Mattress springs offer a sufficient volume of metal that a steel manufacturer in the Hunter region (500,000+ pop.) purchased a mattress recycler to assure access to this feedstock.

Modelling can help local governments and business enterprises in Australia's regional areas to identify priorities and set targets for ramping up their circular economy. The use of environmentally extended input-output models, observation suggests, is limited by the financial resources that Australia's 537 councils are currently committing to the circular economy. In its place, scaling from national data on domestic material consumption and greenhouse gas emissions was attempted in the project described here. The analysis described was undertaken as part of phase 1 of the *City Scan* methodology, developed by a leading international consultancy, Circle Economy in the Netherlands. This 6-month consultancy project was funded mainly by local government entities collaborating to develop the region's circular economy.

The project team encountered large gaps in data at the spatial resolution required that could not be remedied in a convincing way through scaling from national or state level data. For example, estimates were required for consumption of ten categories of materials by industry sector (essentially at the 2-digit ANZSIC level) for the Hunter and Central Coast of New South Wales. Different methods of scaling, *e.g.*, by employment versus by gross value added, yielded results that, for a given material, could differ by more than a factor of 10.

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Keywords: *Circular economy, region, data gaps*

Probabilistic forecasting of wind and solar farm output

John Boland and Sleiman Farah [a]

[a]*Industrial AI, University of South Australia, Mawson Lakes, 5095*

Email: john.boland@unisa.edu.au

Abstract: Accurately forecasting the output of grid connected wind and solar systems is critical to increasing the overall penetration of renewables on the electrical network. This includes not only forecasting the expected level, but also putting error bounds on the forecast. The National Electricity Market (NEM) in Australia operates on a five minute basis. We used statistical forecasting tools to generate forecasts with prediction intervals, trialing them on one wind and one solar farm. In classical time series forecasting, construction of prediction intervals is rudimentary if the error variance is constant - termed homoscedastic. But if the variance changes - either conditionally as with wind farms, or systematically because of diurnal effects as with solar farms - the task is much more complicated. The tools were trained on segments of historical data and then tested on data not used in the training. Results from the testing set showed good performance using metrics including coverage and Winkler score. The methods used can be adapted to various time scales for short term forecasting. The classical time series model has the present value of the output written as a function of past values, including in the case of solar irradiance or power, some seasonal component, plus a noise term.

$$Y_t = f(S_t; R_{t-1}, \dots, R_{t-p}) + Z_t$$

It is hoped that the Z_t are independent and identically distributed (i.i.d) - white noise. It is also hoped that the noise is normally distributed. But, for solar irradiance, wind speeds, and solar and wind farm output - none of these desires is fulfilled. This means that we must cater for the change in distribution or variance over time.

For wind farm output, there is conditional change of variance. If the noise were normally distributed we could simply apply an ARCH or GARCH model to forecast the variance. Since the noise is highly skewed, we apply a normalising transformation and, as it turns out, using exponential smoothing forecasting for the variance works better. For the solar farms, the distribution changes over the day. So we apply the following algorithm.

- If the standard assumptions held, the way to build error bounds around the forecast would be to just to take the standard deviation of the white noise, multiply it by $\pm z$ where the value of z corresponds to the level of probability one wants - eg 1.96 for a 95% prediction interval. Then add those values to the forecast.
- Since the distributions are not normal, one instead finds, for a 95% prediction interval, the 0.025 and 0.975 percentiles of the errors of the process and add them to the forecast.
- Another complication - the error distributions change over the day. So, we perform this process separately for each hour of the day.

Sample Results For the wind farm, the coverage percentages exceeded the expected by 2-3% and widths as measured with the Winkler score were much better than a persistence forecast. For the solar farm, the coverage was almost exactly the expected and once again the widths were narrower than a smart persistence version.

Keywords: *Solar farms, wind farms, probabilistic forecasting, prediction interval, homoscedastic*

Improving transport investment planning in Vietnam

Caroline M. Bruce [a], **Chris Chilcott** [a], **Andrew Higgins** [a], **Stephen McFallan** [a], **Adam McKeown** [a], **Liana Williams** [a], **Rodd Dyer** [b], **Nga Le** [b] **and Huan Le Huu** [c]

[a] *Commonwealth Scientific and Industrial Research Organisation (CSIRO) Australia;* [b] *Focus Group Go Vietnam;* [c] *Northern Mountainous Agriculture and Forestry Science Institute (NOMAFSI) Vietnam*
Email: caroline.bruce@csiro.au

Abstract: Getting products to market where transport infrastructure is underdeveloped or unreliable is a major barrier to agricultural development, particularly in less developed countries. Enhancing connectivity is critical for countries and communities to efficiently access domestic and global markets, to enhance spatial inclusion of remote and rural communities and build resilience in the transport and logistics systems (World Bank, 2019).

CSIRO developed the Transport Network Strategic Investment Tool (TraNSIT) to provide an evidence-based approach for identifying both infrastructure investment that improves transport efficiency and policy changes that reduce transport costs to Australian farmers.

Through a small research project funded by the Australian Centre for International Agricultural Research (ACIAR), the TraNSIT model and other spatial analytics approaches were adapted with a proof-of-concept model developed and applied to a range of different agricultural supply chains (maize, cassava, sugar and coffee) and real-life scenarios in Son La Province, Vietnam. Outputs included quantification of transport costs through the supply chain and identification of transport inefficiencies and at-risk of failure infrastructure.

The scenario modelling provided insights into how transport system changes and impacts are distributed to different supply chain actors, in terms of benefits and adverse or perverse outcomes. The disproportionate proportion logistics and transport costs that fall on the production sector was also quantified.

This project demonstrated how spatial data analytics and optimisation modelling can be applied to complex, real-life transport investment and planning scenarios at different administrative, investment and operating scales within Vietnam. These applications can directly support public and private sector institutions and planners to better analyse problems, evaluate options and allocate resources in ways that reduce transport and logistics costs, and improve connectivity for agricultural value chains, smallholder farmers and rural communities.

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Keywords: *TraNSIT, transport, logistics, agriculture*

Discrete event modeling and simulation of smart parking conflict management

A. Dominici [a] , L. Capocchi [a], E. De Gentili [a] and J-F. Santucci [a]

[a]SPE UMR CNRS 6134, University of Corsica, Campus Grimaldi, 20250 Corte (France)

Email: dominici.antoine.p@gmail.com

Abstract: More cities are choosing to use Smart Parking software tools to solve their parking problems. Due to the price inflation of land within the city centers, adding new parking lots cause more problems then they offer solutions. This is why the solution of providing information to users has become essential. It allows with much less financial means, to ensure that the various car parks already in place can be used to their full potential Lin et al. [2017]. The smart parking approach presented in this paper is a complex discrete-event system whose components can be described by finite state automata reacting to internal or external events. The DEVS Zeigler et al. [2018] (Discrete-EVent system Specification) formalism makes it possible to model this system and to simulate it both in real time and in simulated time.

During our previous research Dominici et al. [2020], a system combining discrete-event simulation and artificial intelligence to determine the time at which a place will be released from its user has been developed. To do this we have classified the different classes according to the estimated time before their release. In this paper, based on our previous work, we want to create a system to direct a driver looking for a place according to the release times of the different places available to him. We must also take into account the competition between drivers wanting to park so that they do not interfere with each other and therefore do not increase the time to find a space due to access conflicts.

To prove that such an approach is possible and interesting to achieve with a discrete-event system, we propose to simulate the evolution of class-based sensors previously constructed in our previous research Dominici et al. [2020]. Then we add a system allowing users to simulate finding a place while being in conflict with other users, all this while applying different conflict management policies in order to determine which would be the most suitable for a real situation.

Each ”Space” atomic models is associated with a class before to start the simulation. This parking slot will change state at regular intervals depending on its class which is modeled using the DEVS time advance function. In our current application, a driver has the ability to search for one (or a set of) place(s) (inside an area) in order to maximize the chances of finding one of them available. In order to simulate the users, we have to create an environment in which a driver can move thanks to a model called ”Travel”. We also need to place the sensors on this virtual environment. Once this is done, each of the instantiated users will therefore move according to one or another strategy to one place. However these can come into conflict by coveting the same place. We have created an atomic model ”Access Conflict Management” which has (according to different policies) to manage potential conflicts occurring during the simulation.

We have therefore done a significant amount of simulation of the evolution of parking spaces for a dynamic and random environment. The simulations were performed with different policies. We noticed that the effectiveness of the policy used depended on the needs. A minimum distance policy will then be more interesting when used in the short term, while a policy taking into account the places chosen and avoiding redundancy and inter-blocking is much more interesting in the long term.

Our results allowed us to see that an application of the simulation in the previous case presented advantages at all points. However the applied policies being too simplistic it does not allow to solve all the problem related to the parking in the cities. In the future, we will therefore have to rely on more advanced methods such as reinforcement learning in order to obtain much more effective policy. We will also try to apply these methods to real cases in the smart parking application which will soon be available in the city.

Keywords: *Discrete-event, modeling, simulation, conflict management, Internet Of Things, smart parking*

CleanGrid – a 100% renewable power supply modelling platform for Australia

Mengyu Li[a], Felix Keck[a] and Manfred Lenzen[a]

[a] *ISA, School of Physics A28, The University of Sydney, NSW 2006, Australia*
Email: mengyu.li@sydney.edu.au

Abstract: The decarbonisation of transport and power supply sectors is key to achieving global and national emissions cut targets in line with Paris Agreement's limiting global warming goals. Electric vehicles (EVs), coupled with large adoption of renewable energy (RE) resources and electrical energy storage in the power system, offer such carbon mitigation solutions. However, due to the unknown spatio-temporal variability of EV charging load and renewable resources, introducing large quantities of EVs and high shares of variable wind and solar energy poses challenges to the load balance management. Due to their ability to meet demand in a short term, battery and dispatchable RE resources including biomass, concentrating solar power (CSP) and hydropower can assist in meeting such supply gaps. Against this background, we develop CleanGrid, a 100% renewable power supply modelling platform for Australia, to examine the potential role of flexible EV loads and diverse energy resources in decarbonisation of the transport and electricity supply sectors.

First, we investigate the spatial and temporal configurations of least-cost 100% renewable power supply in Australia, at various levels of biomass resource use and CSP penetration. We consider the following 6 energy carriers: hydro, biomass, wind, CSP, utility and rooftop PV. To this end, we carry out a high-resolution GIS-based hourly electricity supply-demand matching simulation. We find that, based on the current existing biomass capacity (1.7 GW) installed in Australia, a 100% national RE supply is possible with around 146-148 GW system installed capacity at a levelized cost of electricity (LCoE) of 14-15 A¢/kWh (95% level of confidence). Under a 5-15 times expansion of biomass, the system capacity would be reduced to around 70-110 GW at an LCoE of 9-12 A¢/kWh. Depending on limitations to the generation from biomass posed by competing land uses, CSP could play an important role in reducing the system capacity to nearly 120 GW.

Second, we examine the spatio-temporal interactions of widespread EV charging with a future, 100% renewable electricity system in Australia. We obtain least-cost grid configurations that include both RE generators (hydro, biomass, wind, CSP, utility and rooftop PV) and EVs, the latter under both uncontrolled and controlled charging, and adoption rates between 0 and 100%. We characterise the vehicle-to-grid interaction in terms of overall installed capacity, hourly generation and spillage, LCoE, as well as transmission network expansion topology. We show that supplying 100% renewable electricity to cover current electricity needs in Australia, as well as powering all Australian passenger vehicles as controlled-charged EVs, requires 205 GW of installed capacity (8 GW from hydro, 2.1 from biomass,70 GW from wind, 41 GW from utility PV,81 GW from CSP, and 3.1 GW from rooftop PV) at an LCOE of 14.7 AUD¢/kWh. This 100% RE supply with EV charging leads to a reduction in electricity cost of 1,086 AUD/capita annually, comparing to the current annual expenditure for electricity and conventional vehicle fuel.

Third, we investigate the impact of battery energy storage on renewable energy supply in Australia. Electrical energy storage (EES) has the potential to enable a transition to clean energy in the future as it brings flexibility into the electricity network. Uncertainties exist around EES regarding technology, costs, business models and market structures but agree on EES being beneficial in improving grid stability. Our study offers an economic analysis of the role of EES in low-carbon electricity. A GIS-supported hourly simulation study of Australia assesses the impact of adding EES to wind and solar utilities, on LCoE, installed capacity, generation mix and energy spillage. The study finds that EES deployment is able to lower LCoE in scenarios with high penetration of renewable sources. In the case study of Australia, it is found that EES between 90 and 180 GWh capacity can be economic for cost levels below 1,000 AU$/kWh. In addition, the study finds that EES can reduce LCoE by 13-22%, reduce installed capacity by up to 22%, and reduce spilled energy by up to 76%. It is shown that the generation mix is highly influenced by the magnitude of EES deployed.

Keywords: *Low-carbon electricity supply, electric vehicles, biomass, battery*

Impacts of groundwater and soil types on building ground-coupled heat loss

Zhengen Ren, **Melissa James and Dong Chen**

CSIRO Energy, Private Bag 10 Clayton South, Vic 3169, Australia
Email: zhengen.ren@csiro.au
melissa.james@csiro.au; dong.chen@csiro.au

Abstract: Heat loss through a building foundation has a significant impact on residential building energy consumption for space heating and cooling as the above-grade components of the building fabric are built more energy efficient. Nowadays, for a well-built house the ground-coupled heat losses can account for 30% to 50% of the total heat loss, showing the importance of a detailed analysis of ground-coupled heat transfer (GCHT). GCHT is a complex three dimensional (3D) transient heat transfer phenomenon. Ground-coupled heat loss can be significantly impacted by groundwater, soil thermal conductivity and ground surface conditions.

For transient heat transfer through building grounds, a number of ground-coupled heat loss models have been developed over the past five decades. However, few studies have been conducted to model the impacts of groundwater on GCHT in detail, especially for the foundations with 3D transient conditions.

In this study, a commercial 3D transient heat transfer program was applied to simulate GCHT for thousands of foundation configurations, which consider foundation shapes and sizes, insulation configurations, groundwater table and soil types.

The results from this study showed that for a slab-on-ground floor with a size of 400 m^2 and average soil properties and three levels of horizontal insulation to the slab, the annual mean heat loss through the floor without insulation increased by 54%, 24%, 8% and 3% when there was a water table at depths of 3m, 5m, 9m, and 12m respectively, by 40%, 19%, 6% and 3% with R1 insulation to the slab, and by 21%, 11%, 4% and 2% with R4 insulation to the slab. As expected, the impacts become less with the increase in the water table depth and insulation R value.

Keywords: *Heat loss, building foundation, 3D numerical analysis, groundwater table, soil type*

Mapping future transport passages for proposed shale gas development in NT: an application of TraNSIT

Nicholas B. Smolanko, Caroline Bruce, Stephen McFallan, Andrew Higgins, Artiom Bondarenco and Adam McKeown

Commonwealth Scientific and Industrial Research Organisation (CSIRO), Adelaide, 5064, Australia
Email: nick.smolanko@csiro.au

Abstract: The Transport Network Strategic Investment Tool (TraNSIT) was used to analyse proposed shale gas development in the Beetaloo Sub-basin, Northern Territory (NT). TraNSIT was developed by CSIRO over the past nine years with significant input from over 400 industry organisations, associations, and government agencies. The tool has mapped supply chains for over 140 commodities in Australia, accommodating 520,000 enterprises and nearly a million supply chain paths. Analytical tools like TraNSIT are an important tool to inform communities, government and industry on the impacts of freight movements. The results from the tool can help highlight options for future infrastructure investments.

The Beetaloo Sub-basin is located in a remote part of the Northern Territory (NT), serviced by a limited number of major roads and the Adelaide to Darwin rail network. The construction and operational phases of onshore gas development in the Sub-basin could significantly impact freight volumes along the regional transport network. A goal of this project was to understand these potential changes on the established road and rail networks, relative to current freight movements.

The project investigated potential onshore gas development due to construction and operational phases, split into four transport movement stages: construction during years 1 and 2, average drilling and fracking operations, and peak operations. These stages were then compared against the baseline of current freight movements moving within, to, from or through the Beetaloo Sub-basin, and economic metrics produced. 'What if' scenarios and critical link analyses were also run, to further examine potential impacts.

The baseline analysis determined there are 81 unique commodities which require 108,286 trailers to move 2.35 million tonnes of annual freight with a transport cost of $424 million. For the construction year 1 phase, 608,175 tonnes of additional freight relating to gas development were transported in or out of the Beetaloo Sub-basin or to parts of the national gas pipeline network projected to require expansion, duplication or construction. Pipes for this national network comprised most of this freight. Within the Beetaloo region, these additional freight movements resulted in a freight volume increase of roughly 20 percent along the Stuart highway, more than 30 percent along the Carpentaria Highway and over 100 percent along some sections of the Gorrie Dry River Road. Construction year 2 freight volumes are about 30 percent of the demands in construction year 1, with a majority being freight of pipes for the local gathering network.

Three 'what if' scenarios within the Beetaloo Sub-basin were modelled, based on stakeholder input, examining network and supply chain changes. One of the scenarios investigated a network change, with a selection of roads cut for four months during the wet season. This network change resulted in significantly longer trips, with some trips being 2.5 times longer than their respective baseline trip. These longer trips incurred increased freight costs, in some cases by more than 150 percent compared with their baseline trips.

Future work through TraNSIT on the Beetaloo Sub-basin could examine further supply chain changes or analyse potential bottlenecks where infrastructure capacity is insufficient.

Keywords: *Freight movements, transport systems, infrastructure modelling, Beetaloo Sub-basin, TraNSIT*

Wave energy production in the Sardinia Western coast: current status and future prospects

A. Sulis[1], **Michael Henriksen**[2], **Peter N. Svendsen**[2] **and S. Serreli**[1]

[1] *Dept. of Architecture, Design and Urban planning (DADU), University of Sassari, Sassari, Italy*
[2] *Wavepiston A/S, Helsingør, Denmark*
Email: asulis@uniss.it

Abstract: Wave energy is a renewable and pollution-free energy source that has the potential for a substantial contribution in the EU energy market. The EU industry is the global leader for developing ocean energy technologies, mainly wave and tidal. Ocean energy technologies are relatively stable and predictable, and can complement fixed and floating offshore wind. The EU Communication (EC, 2020) proposed an ocean energy strategy where different technologies should suit different sea basins. The variety and complementarity of European sea basins create a unique worldwide position, but different technologies development and commercial levels have become too large across European basins. While the North Sea is currently the world's leading region for deployed capacity and expertise in waves, the good potential for wave energy in the Mediterranean Sea is far to be properly used and wave technologies are still pilot and in demonstration phase.

Recently, extensive and accurate estimates of wave energy along the Mediterranean coasts have been provided by many authors. Estimates of the available mean power (Pm) in kW/m and the related potential energy production suggests that an energy hotspot is located in the Western coasts of Sardinia (Italy) (Vicinanza et al., 2011) with Pm = 11.4 kW/m. The main aim of the proposed research is to demonstrate that a proper selection and customization of a Wave Energy Converter (WEC) operating in an EU oceanic basin with greater energy potential could produce profitable power output in the Western coasts of Sardinia. Specifically, the assessment of the energy potential in the hotspot located offshore of the city of Alghero and the comparisons between the simulated WEC energy productivities in Alghero and in the North Sea will be presented.

The content of the presentation will be of evident interest for Sardinian communities that want to invest in this field and thus need to optimize the WEC for specific wave climate in order to reach the level of commercial maturity.

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Keywords: *Wave energy, Wave Energy Converters, Sardinia coast*

Value-of-information analysis: A mathematical toolkit connecting models, monitoring and decision-making

Matthew P. Adams [a,b], **Kate J. Helmstedt** [a], **Sarah A. Vollert** [a], **Ryan F. Heneghan** [a], **Michael Bode** [a] **and Hui Xiao** [c]

[a] *School of Mathematical Sciences, ARC Centre of Excellence for Mathematical and Statistical Frontiers, and the Centre for Data Science, Queensland University of Technology, Brisbane QLD Australia*
[b] *School of Chemical Engineering, The University of Queensland, St Lucia QLD Australia*
[c] *School of Life and Environmental Sciences, Deakin University, Burwood VIC 3125, Australia*
Email: mp.adams@qut.edu.au

Abstract: Models, which describe a system of interest, are proposed to be useful for decision-making. To use a model for decision-making, typically different scenarios of the model are run. Each of these different scenarios represents a different decision. Ideally, the predictions of these scenarios are sufficiently distinguishable from each other so that the best decision is obvious. However, even if the forecasts are difficult to distinguish from each other, they still may be sufficiently useful to inform decision-making (Adams et al. 2020).

Monitoring the system of interest can yield information that provides evidence for or against different model structures or parameterisations. Ideally, monitoring data is of sufficient quality and appropriate format that it can be used to reduce uncertainty in model parameters either directly (i.e. as a measurement of the model parameters) or indirectly (e.g. comparable to a model output so usable for model-data calibration). However, monitoring data is not guaranteed to improve models or the decisions made based on the forecasts they can provide – it could be that the information provided by the data is ultimately redundant for these purposes (McDonald-Madden et al. 2010). Monitoring can also be expensive and time-consuming, so a question of broad interest is to identify the value of the information new monitoring data can provide – especially in the context of whether this new data may change decision-making or not.

This talk provides an overview of "value-of-information analysis" (Canessa et al. 2015, Xiao et al. 2020) – and demonstrates that it provides a mathematical toolkit for connecting models, monitoring and decision-making. Specifically, this analysis identifies how valuable a potential new measurement may be for its ability to change decision-making. This is especially vital in applications where monitoring data is scarce and difficult to obtain, so decisions about collecting this new data must be made carefully. Tutorial examples of how value-of-information analysis works, and the kinds of conclusions that can be obtained, are provided. These examples will be primarily focused on ecological systems that can be represented as a network, but the same techniques have potential application in any system where it is the combination of modelling and data that aims to support decision making.

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Keywords: *Calibration, decision making, predictions, uncertainty analysis, value-of-information*

Bayesian networks as a tool estimating the risk and benefits of COVID-19 vaccines

Helen J. Mayfield[1], Colleen L. Lau[1], Andrew Baird[2], Samuel Brown[3], Anoop K Enjetic[4], John Litt[5,6], Jane Sinclair[3], Kirsty Short[3], Hassan Vally[7], Aapeli Vuorinen[8], Michael Waller[1] and Kerrie Mengersen[9]

[1]School of Public Health, Faculty of Medicine, The University of Queensland, Australia, [2]St Kilda Medical Group, St Kilda, Victoria, Australia, [3] School of Chemistry and Molecular Biosciences, Faculty of Science, The University of Queensland, Brisbane, Australia. [4] School Of Medicine and Public Health, University of Newcastle, Callaghan, NSW; Calvary Mater Newcastle Hospital ,Waratah and NSW Health Pathology John Hunter Hospital, New Lambton Heights, NSW, [5] Discipline of General Practice, College of Medicine and Public Health, Flinders University, Adelaide, Australia. [6] Immunisation Coalition, Melbourne, Victoria, Australia, [7] LaTrobe University, VIC, Australia, [8] Department of Industrial Engineering and Operations Research, Columbia University, New York, NY 10027, USA, [9]School of Mathematical Sciences, Faculty of Science, Queensland University of Technology, Brisbane, Queensland, Australia
Email: h.mayfield@uq.edu.au

Abstract: Confusion surrounding the safety of the COVID-19 AstraZeneca (AZ) vaccine in relation to fatalities from rare, atypical blood clots (thrombosis and thrombocytopenia syndrome [TTS]) has contributed to increased vaccine hesitancy in Australia. For those attempting to make an informed decision regarding the AZ vaccine, communication in the media summarising the current research can lack transparency, often fails to compare relevant counter-factual scenarios in a meaningful way, and is not always based on the best available evidence. The increasing number of scientific studies and data sources that present findings on only a single piece of the overall puzzle also adds to this challenge.

A risk-benefit analysis framework is therefore urgently needed to reduce this uncertainty by combining and effectively communicating the risks and benefits of the AZ vaccine. To be effective, it is crucial that this framework is both transparent in its assumptions and data sources, as well as easily updatable to account for both new evidence and changes in the pandemic landscape, such as new virus variants or vaccines, or changes in the rates of community transmission. It must also be able to incorporate data from a wide range of data sources, and in different formats.

Bayesian networks can provide the ideal framework for synthesizing the evidence from various sources including local and international data, government reports, published literature and expert opinion, into a probabilistic model that is both interactive and transparent. Here, we describe the methods used to design and implement a Bayesian network model that collates the best available evidence to compare the risks versus benefits of the AZ vaccine in the Australian context. Expert judgement was used to interpret the available evidence to determine the structure of the model, the relevant variables, the data to be included and how these data are used to inform the model. By using a network structure to link evidence from various data sources, the model can be used to generate scenarios comparing the risk of dying from TTS following the AZ COVID-19 vaccine with the risk of dying from COVID-19 or COVID-19 associated blood clots. We also show how the same modelling process can be used to create an equivalent risk-benefit network model for the Pfizer vaccine and the risk of myocarditis and pericarditis.

Keywords: *Bayesian networks, COVID-19 vaccine, vaccine hesitancy, risk-benefit analysis*

Keeping models as (un)certain as we are: ecological forecasts from process-based models calibrated to observed data using Bayesian inference

G.M. Monsalve-Bravo, [a,b] **M.P. Adams** [c,d,e,f]**, N. Dexter**[g] **and E. McDonald-Madden**[a,b]

[a]*School of Earth and Environmental Sciences, The University of Queensland, St Lucia, QLD 4072, Australia*
[b]*Centre for Biodiversity and Conservation Science, The University of Queensland, St Lucia, QLD 4072, Australia*

[c]*Centre for Data Science, Queensland University of Technology, Brisbane, QLD 4001, Australia*
[d]*ARC Centre of Excellence for Mathematical and Statistical Frontiers, Queensland University of Technology, Brisbane, QLD 4001, Australia*

[e]*School of Mathematical Sciences, Queensland University of Technology, Brisbane, QLD 4001, Australia*
[f]*School of Chemical Engineering, The University of Queensland, St Lucia, QLD 4072, Australia*
[g]*Booderee National Park, Village Road, Jervis Bay, NSW 2540*
Email: g.monsalvebravo@uq.edu.au

Abstract: Data-driven modeling is proposed as a means to produce forecasts that can inform decision-making. This goal is already realized in the field of weather science. However, in ecology, it 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. Models used for these forecasts are often considered to be "sloppy"; that is, some of the model parameters are more important to determine than others, for precision in forecasting; nonetheless, we may not know how to identify these important parameters. Given these difficulties, 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 model predictions, including uncertainty, that are useful for informing environmental decisions (Adams et al., 2020a). Bayesian inference is used for model-data calibration, and its implementation is carried out via Sequential Monte Carlo sampling (Adams et al., 2020b); an ensemble method that extends upon concepts used in Markov Chain Monte Carlo sampling. A key by-product 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.

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Keywords: *Uncertainty quantification & propagation, ecosystem network modeling, Bayesian inference*

Unpacking wicked health problems using Bayesian Network Modelling

Esther A. Onyango[a] **and Oz Sahin**[b]

[a] Centre for Planetary Health and Food Security, Griffith University, Brisbane, 4111, Australia
[b] School of Engineering, Griffith University, Gold Coast, 4112, Australia
Email: e.onyango@griffith.edu.au

Abstract: According to the recent IPCC we are well on track to exceed the 1.5 C warming threshold in this century unless we act fast to reduce emissions (IPCC, 2021). Projected warming and other changes in the climate system will impact on communities and health systems through multiple interrelated causal pathways. The burden of many climate-sensitive health risks are projected to increase under warming and the focus is on solutions for risk reductions. Exposure to climate hazards will result in differential health outcomes and affect communities and health systems in varying degrees depending on vulnerability factors and the health system resilience. Protecting vulnerable communities requires first an understanding of the complexity of the multiple influencing biophysical, socio-economic and socio-cultural factors that interact to determine risks to communities, developing integrated assessments to determine exposure and vulnerability to develop adaptive capacities, otherwise known as "wicked problems".

In this presentation we explore the utility of Bayesian Network (BN) models in unpacking impacting factors and intervention options for wicked climate change and health problems. BNs have several advantages over biological/process-based or statistical models: i) BNs express probabilistic distributions and thus can handle uncertainty; ii) they can incorporate a variety of data from different sources; iii) qualitative expert judgements can be used to fill in missing data; iv) they are dynamic and allow for integration of new or updated data to reflect changing conditions; v) the BN network allows for visualisation of important variables and drivers in the system and their associated cause-effect relationships, vi) the process of building the model is participatory, therefore stakeholders opinions and priorities can be integrated from the onset and vii) they are suited to decision-making; involving policy-makers in modelling potential impacts of interventions may lead to better outcomes and improvements in climate change and malaria risk management policies.

Using a case study of climate change and malaria transmission risk, we demonstrate how BNs can be used to provide a robust understanding the complex interrelationships underlying wicked climate change and health problems. We further demonstrate the applicability of BNs for modelling hierarchical relationships in epidemiological studies and health impacts where there are many inter-related pathways of causality. Finally, we demonstrate the suitability for BN's to improve decision-making process in public health systems particularly in situations where cause-effect relationships are critical in informing decision outcomes.

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Keywords: *Climate change and human health, wicked problems, Bayesian network modelling, decision-support tools*

Model selection and sloppiness in ecology

S. A. Vollert[a,b], **R. Salomone**[a,b], **G. Monsalve-Bravo**[cd], **M. P. Adams**[a,b,e], **and D. J. Warne**[a,b]

[a]School of Mathematical Sciences, Queensland University of Technology (QUT), [b]Centre for Data Science, QUT, [c]School of Earth and Environmental Sciences, The University of Queensland (UQ), [d]Centre for Biodiversity and Conservation Science, UQ, [e]School of Chemical Engineering, UQ
Email: sarah.vollert@connect.qut.edu.au

Abstract: In ecology, model selection is important for making sure that models used for conservation and management decisions are not overly impaired by model structure uncertainty. However, the most widely used model selection metrics in ecological modelling, such as the Akaike information criterion (AIC) or the Bayesian information criterion (BIC), utilise simple measures for penalising complexity that heavily rely on asymptotic results for large sample sizes (Gelman et al., 2014). While these standard complexity measures are straightforward to implement, they do not account for the complex dependencies between model parameters that are particularly common in ecological models.

Analyses of both model sloppiness and parameter identifiability can provide insights into a key challenge for practical model selection, that is, the quantification of multi-parameter model complexity (Browning et al., 2020; Transtrum et al., 2015). Both analyses, based on spectral properties of the Fisher Information Matrix, seek to characterise the sensitivity of the model outputs to changes in parameter values and thus can reveal critical combinations of parameters, weighted by their influence on model outputs. These weighted combinations in parameter space provide scope for an intrinsic measure for multi-parameter model complexity, which can be exploited for model selection, model reduction, and even future data collection efforts.

In this work, we demonstrate the connection between the principles of model sloppiness and the Laplace approximation of the Bayesian posterior model probability that reduces to the BIC in the large sample limit (Neath and Cavaneugh, 2012). This link has not been previously identified; however, this non-asymptotic form has potential benefit in the all-too-common case where very few noisy observations are available to calibrate complex models possessing many parameters requiring estimation.

To this end, we explore the utility of model sloppiness analysis in combination with information criteria for robust model selection when models have realistic sample sizes for ecological time-varying datasets. Through simulations, we investigate the performance of these methods for ecological models based on ordinary differential equations, highly relevant in ecological conservation to guide ecosystem management and risk assessment. We highlight several important scenarios where accounting for model sloppiness detects the true model more frequently for small numbers of observations. As a result, this work provides practical guidelines for using model selection metrics in the landscape of ecological models and demonstrates that accounting for model sloppiness and parameter identifiability is essential for realistic applications in ecology.

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Keywords: *Information criterion, model selection, model sloppiness, ecological models*

EXTENDED ABSTRACT ONLY

Novel multi-objective optimization modeling for permeable breakwaters

Mostafa Gandomi [a], Mohammad Reza Nikoo [c], Banafsheh Nematollahi [b] and Amir H. Gandomi [d]

[a]*Ph.D. Student of Marine Structures, Faculty of Civil Engineering, University of Tehran, Tehran, Iran. Email: mostafa.gandomi@ut.ac.ir*

[b]*Ph.D. Candidate, Department of Civil and Environmental Engineering, Shiraz University, Shiraz, Iran. Email: b.nematollahi@shirazu.ac.ir*

[c]*Associate Professor, Department of Civil and Architectural Engineering, Sultan Qaboos University, Muscat, Oman. Email: m.reza@squ.edu.om*

[d]*Professor, Faculty of Engineering & IT, University of Technology Sydney, Ultimo, NSW 2007, Australia. Email: gandomi@uts.edu.au*

Abstract: Strategic beaches locations for industrial, recreational, and residential applications highlight the need for constructing practical cost-efficient protective structures with negligible destructive effects on the environment (Rageh and Koraim, 2010). Permeable breakwaters provide beneficial manufactures for harbours' safekeeping by eliminating conventional breakwaters issues. However, despite the permeable breakwaters' advantage over the conventional ones, they have been paid less attention in the literature since their complex systems cause ambiguity to study their behaviours. To cope with these complexities, this study develops a novel multi-objective optimization model based on a non-dominated sorting genetic algorithm- II (NSGA-II) considering an outstanding risk assessment for wave characteristics inherent uncertainties to optimize the wave reflection and transmission coefficients as well as the rock volume included in the breakwater system.

The presented risk-based multi-objective optimization model is applied to a developed machine learning model derived based on the results of experimental studies carried out on an innovative permeable breakwater structure consisting of two vertical porous walls separated by rockfill material (Fig. 1). These experiments are conducted in the laboratory of the Soil Conservation and Watershed Management Research Institute (SCWMRI) of the Ministry of Agriculture, Iran. To apply the machine learning algorithms, the dimensionless parameters of permeable breakwater configuration and wave spectrum are used for modelling the reflection and transition coefficients as representatives of the breakwater hydrodynamic behaviour since modelling the hydraulic behaviour of these structures is a non-linear problem (Gandomi et al., 2020). The presented risk-based multi-objective optimization model results indicate that the proposed novel permeable breakwater can be often used in ports effectively with a high level of reliability, considering the allowable waves ranges to deal with the risks concerned to the incident waves characteristics.

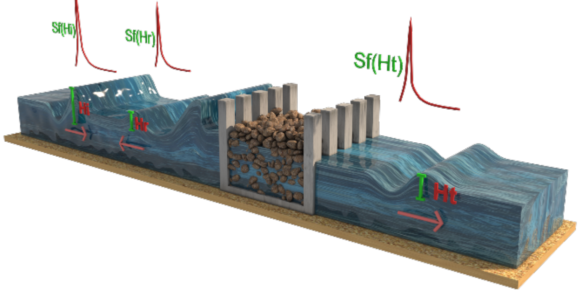

Figure 1. Schematic diagram of the proposed preamble breakwater

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Keywords: *Risk-based multi-objective optimization, experimental data, permeable breakwater, machine learning methods*

Developing calibration models for low-cost air-quality monitors

C. Lee[a], G. Kaur[a], H. Wang[a], J. Zhao[a], B. Chiera[a], T. Menadue[b], A. Walsh[b] and L.A. Ward[a]

[a] *UniSA STEM, University of South Australia, Mawson Lakes, SA 5095*
[b] *Department for Energy and Mining, Government of South Australia, GPO Box 320, Adelaide, SA 5001*
Email: leecs016@mymail.unisa.edu.au, zhajy163@mymail.unisa.edu.au

Abstract: The Department for Energy and Mining (DEM) is the lead agency for environmental regulation of the mineral resources industry in South Australia. Mines and quarries can generate dust in the air, which can lead to potential health and nuisance impacts. Air-quality monitors can be a useful tool for mine and quarry operators to demonstrate that they are achieving environmental standards for air quality. Gravimetric air-quality monitors, such as Beta Attenuation Mass Monitors (BAMs) and Tapered Element Oscillation Microbalance monitors (TEOMs), are certified for use as compliance monitors due to their high accuracy but may be prohibitively expensive for smaller scale mine and quarry operators. Optical air-quality monitors such as AQ MeshPod, ADR1500 Nephelometer and Purple Air monitors provide a more affordable option, but are much less accurate and are generally not considered suitable for compliance monitoring against public health measurement criteria.

To improve the utility of optical monitors as a regulatory and dust management tool, we have tested several methods for post-processing air-quality data from optical monitors to make it match the gravimetric air-quality data more closely. The methods we tested include the machine-learning techniques of k-Nearest Neighbours (kNNs), Random Forests (RFs) and Neural Networks (NNs), as well as Multivariate Adaptive Regression Splines (MARS) which builds on DEM's initial linear regression modelling. The models were developed using recent data sets provided by DEM for three locations where gravimetric monitors, optical monitors and weather stations were co-located close to operational quarries.

It was identified through a review of academic literature and from preliminary linear regression modelling that optical air-quality monitor data may be affected by environmental factors such as humidity and temperature. These, and other, environmental factors were included as predictor variables into the models, and the machine-learning algorithms were able to incorporate these predictors to improve the accuracy of the predicted values of the concentration of particulate matter against the actual measurements.

We also investigated several performance metrics to assess how well the post-processing machine-learning methods calibrate the optical monitor data, especially during periods of elevated dust concentrations.

Our results establish a proof-of-concept that we can post-process low-cost optical monitor data to gain a higher level of accuracy, and to improve the optical monitors as a regulatory and dust management tool, thus opening the door to an affordable but effective monitoring option for the mineral resources industry and potentially other industries.

This work was done as a UniSA Mathematics Clinic student project with Liaisons Terry Menadue and Alistair Walsh from DEM and academic staff Belinda Chiera and Lesley Ward from UniSA.

Keywords: *Gravimetric air-quality monitors, optical air-quality monitors, calibration models, machine learning methods, K-Nearest Neighbours*

Wood damage detection and classification via contact ultrasonic testing and machine learning algorithms

Mohsen Mousavi and **Amir H. Gandomi**

Faculty of Engineering and IT, University of Technology Sydney, Ultimo, NSW 2007, Australia
(Emails: Mohsen.Mousavi@uts.edu.au, Gandomi@uts.edu.au)

Abstract: Studying defects in wood is of great interest to many fields of real-life applications such as the construction industry, wooden-pole inspection, historical building assessment, mechanised harvesting industry. For instance, it is crucial to characterise the mechanical properties of wooden boards in the construction industry. Similarly, wooden poles inspection is of great importance as it can ensure the integrity of poles in withstanding different loading scenarios such as wind load, as deteriorated poles can undergo a sudden collapse causing fire ignition or power outage in a network. Historical buildings are precious human asset that are required to be monitored regularly. A great number of such buildings are made of wooden materials and thus need to be monitored for defects to uphold their healthy condition. Mechanised harvesting is also an industry section that benefits a lot from quality assessment of standing trees. The reason lies within the fact that defective trees are not suitable for industry purposes and will only end up being used as sawlogs. Therefore, identification of such trees can prevent their cutting-down which is also an environmentally friendly act. As such, it is vital to identify defects of any type in wood to prevent the occurrence of catastrophic incidents.

This study makes the use of the contact Ultrasonic Testing (UT) technique (as a sensing technology) in conjunction with signal processing and machine learning algorithms for classification and characterisation of defects in wood materials. Feature engineering is an important part of any machine learning algorithm. As such, in this study, an advanced signal decomposition algorithm, termed Variational Mode Decomposition (VMD) (Dragomiretskiy & Zosso (2014)), was used to extract some informative features out of the recorded raw ultrasonic signals. The derived features were then fed into several machine learning algorithms to solve the problem of the classification of woods based on several aspects of the wood and the testing regime, including the type of wood, the direction of the ultrasonic test with respect to the growth rings of the wood, and the health condition of the wood specimens (Mousavi & Gandomi (2021)). The results demonstrate the high performance of the proposed strategy for classification of wood based on such characteristics. Several lab and field trials were conducted to demonstrate the capability of the proposed strategy. The results of this study pave the way for damage detection and classification in wood materials regarding the aforementioned applications. The developed strategy is also resilient to any challenge that contact ultrasonic sensing regime may face. These include uncertainties stemming from the amount of the couplant gel applied to the surfaces of the studied wooden specimen at the receiver and transducer sides, the amount of the pressure applied to the transducer and receiver, and any misalignment of the transducer and receiver. The results show the high classification performance of the proposed strategy where almost a 100% -fold cross-validation accuracy was achieved as for the lab trials, and above 93% accuracy was achieved regarding the field trials.

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Keywords: *Ultrasonics, signal processing, machine learning, variational mode decomposition, wood-hole defect, non-destructive damage testing*

Structural condition monitoring under environmental and operational variations effect

Mohsen Mousavi and **Amir H. Gandomi**

Faculty of Engineering and IT, University of Technology Sydney, Ultimo, NSW 2007, Australia
(Emails: Mohsen.Mousavi@uts.edu.au, Gandomi@uts.edu.au)

Abstract: Structural condition monitoring under Environmental and Operational Variations (EOV) is a challenging task due to the effects of EOV on structural responses that can mask any signs of damage in those signals. There are generally two types of techniques based on data used for condition monitoring of structures: (1) output-only methods, and input-output methods. The former is only reliant on information from structural responses either in the time domain or frequency domain. However, the latter methods require information from the EOV effects, such as temperature variations. Both techniques have been widely studied by researchers. The most critical part of such algorithms is to develop a strategy that can reduce or ideally omit the unwanted effects of the EOV on the structural responses, whereby the structural condition monitoring task could be turned into a much simpler practice. Such techniques thus include several steps: (1) a step designed to reduce or remove the effect of the EOV on the structural responses, (2) a step designed to fuse the obtained EOV-effect-free signals for constructing an error signal, (3) A threshold setting step that can be used to monitor the time of damage initiation for realtime condition monitoring. The above three steps are sometimes accompanied by a machine learning algorithm trained on the healthy state of the structure to enhance the effect of data fusion through seeking prediction errors as damage sensitive feature (DSF). Two different output-only condition monitoring methods are presented. The proposed methods require a couple of lowest structural natural frequencies, identified from the structural vibration response, over a long period of time. An advanced signal processing algorithm, termed Variational Mode Decomposition (VMD) (Dragomiretskiy & Zosso 2014) was exploited to address the first step through decomposing the structural natural frequency signals into their oscillatory modes, termed Intrinsic Mode Functions (IMFs). Knowing that damage introduces a long-lasting change to the structural responses, the mode corresponding to the temporal variations of the natural frequencies are excluded from further study. Therefore, while any unwanted hard-to-predict EOV effects are excluded, the information about the damage state is retained. The VMD algorithm was also used for denoising the frequency signals to reduce the effect of noise on condition monitoring results. Then, Johansen cointegration was employed to obtain a stationary signal out of a set of non-stationary IMFs of the structural responses (Mousavi & Gandomi 2021a). The obtained stationary signal (target) along with the non-stationary IMFs (features) corresponding to the healthy state of the structure were used to train a Long-Short-Term Memory (LSTM) model, in order to learn the rule behind Johansen cointegration. The prediction error of the trained model was considered as a damage sensitive feature. Likewise, the VMD algorithm was used for the same purpose in the second study. Then, The FastMCD algorithm was employed to obtain robust location and scatter of the dataset corresponding to the healthy state of the structure (Mousavi & Gandomi 2021b). Next, a Bidirectional LSTM (BiLSTM) architecture was trained on the obtained Mahalanobis distances (target) of the first IMFs of the structural natural frequencies (features), corresponding to the healthy state of the structure, from their identified location. The error associated with further prediction on new observations was taken as a DSF. A threshold was obtained for the errors based on the concept of R-charts in this work. A numerical example, as well as benchmark problems, were solved to demonstrate the capability of the proposed methods.

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Keywords: *Condition monitoring, environmental and operational variations, variational mode decomposition, structural natural frequency, temperature variations*

SINFERS: A Soil Inference System with automatic uncertainty propagation

J. Padarian, E. Jones, A.B McBratney and B. Minasny

Sydney Institute of Agriculture & School of Life and Environmental Sciences,
The University of Sydney, New South Wales, Australia
Email: jose.padarian@sydney.edu.au

Abstract: A soil inference system is a software engine for the systematic prediction of soil properties from other soil properties readily available. It consists of a collection of pedotransfer functions (PTFs) which are the knowledge rules that drive the inference process. Given a user input (records with values of one or more soil properties; or measurements from a sensor), SINFERS starts by predicting soil properties using all possible combinations of inputs and PTFs, assessing the uncertainty of each prediction. Then, a new round of predictions is started, using the input and predicted properties, automatically propagating the uncertainty at each step. This process continues until all the combinations of soil properties and PTFs are exhausted (Figure 1). During this process, SINFERS also identifies when new predictions are outside the data domain in which the PTFs were generated, penalising the uncertainty in the presence of extrapolations. SINFERS provides a way of organising knowledge in a carefully curated collection of PTFs that fulfil the requirements needed for uncertainty assessment. Additionally, it provides a systematic and consistent way of executing PTFs and applying uncertainty propagation. This tight coupling of model and uncertainty assessment ensures the correct use of PTFs. By using such a system, PTFs can be well documented and organised, not just in a journal paper, and thus promoting their use. It also opens the possibility of integration with other systems such as handheld devices (e.g. spectrometers) that can be used directly in the laboratory and the field to generate multiple predictions from a single reading.

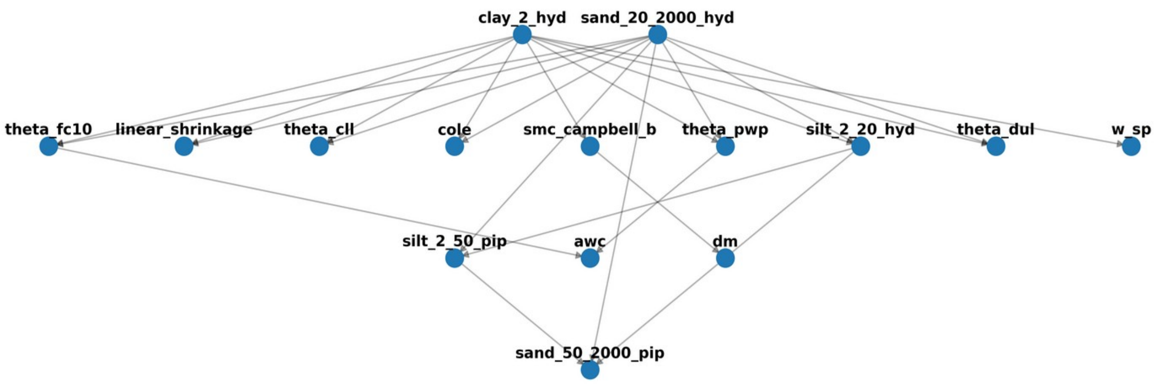

Figure 1. Example of the sequence of pedotransfer functions triggered by two soil properties (clay and sand content).

Keywords: *Symbolic regression, pedotransfer functions, uncertainty propagation, soil modelling*

Two-equation turbulence modelling of open channels

Ahmad Sana [a]

[a] *Department of Civil and Architectural Engineering, Sultan Qaboos University, PO Box 33 Muscat, 123, Oman*
Email: sana@squ.edu.om

Abstract: The transport of sediment and pollutants in open channels essentially depend on the turbulence phenomenon among other factors. Being the most complex phenomenon to fully comprehend and estimate, turbulence computations have been the most challenging part of engineering calculations. Several analytical and empirical models have been in vogue, prior to the widespread availability of powerful computing facilities, to estimate turbulent boundary layer properties. However, this practice changed approximately four decades ago when a few turbulence models started to emerge and initially gained popularity among the researchers and then among the practicing engineers. Almost all the present-day commercial models, used for engineering calculations for rivers and estuaries include some of these turbulence models. Nonetheless, many engineering calculations are based on empirical models or a combination of turbulence and empirical models yet. As usual, turbulence models used in research are far more complex and computationally expensive than the ones used in the field applications. Several studies on open channels based on Direct Numerical Simulation (DNS), Large Eddy Simulation (LES) and Reynolds Stress models have been carried out in the past. However, two-equation turbulence models have gained popularity among researchers as well as practicing engineers because of their reasonable accuracy with computational economy. Many versions of such models are reported in the literature among them k-epsilon and k-omega have been the most popular two-equation models. Sana et al. (2009) and Sana and Tanaka (2000, 2010) have compared the performance of some of the popular versions of two-equation turbulence models in case of oscillatory boundary layers. In this paper, a few model versions are reviewed based on their predictive abilities and computational economy against the well-known bottom boundary layer properties in open channels. Qualitative and quantitative comparisons have been made to infer that the choice of model versions should be based on the field application. For example, the bottom shear stress is very well predicted by the k-omega model whereas the cross-stream velocity profile and turbulent kinetic energy are predicted more efficiently by k-epsilon model versions. Consequently k-omega model will be more appropriate for estimating bottom sediment transport whereas k-epsilon model is expected to yield better results in case of suspended sediment or pollutant mixing and transport in the field. This study may be useful for the researchers and practicing engineers in selecting a suitable two-equation model for calculating various bottom boundary layer properties.

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Keywords: *Turbulence modelling, open channel flow, bottom shear stress, two-equation model*

The estimation of multi-layer flash flows using machine learning systems

Foad Vosoughi [a], **Mohammad Reza Nikoo** [b] **and Amir H. Gandomi** [c]

[a] *Research Associate, Department of Civil and Environmental Engineering, Shiraz University, Shiraz, Iran. Email: foad.vosooghi@gmail.com*

[b] *Associate professor, Department of Civil and Architectural Engineering, Sultan Qaboos University, Muscat, Oman. Email: m.reza@squ.edu.om*

[c] *Professor, Faculty of Engineering and Information Technology, University of Technology Sydney, Ultimo, NSW 2007, Australia. Email: gandomi@uts.edu.au*

Abstract: The accurate prediction of multi-layer flash flood characteristics following dams' sudden failure is essential for disaster prevention and mitigation. Results of dam-break flash flooding may also be utilized to analyse other natural phenomena such as tsunamis and landslides in water reservoirs. Upstream (reservoir) sediment deposition and downstream hydraulic conditions may substantially influence such flash flood incidents. The current study was motivated by the apparent lack in the literature of any study on evaluating the efficacy of expert systems to represent such multi-layer debris flows over dry-bed and wet-bed initial tailwater portion or downriver with semi-circular barriers.

Accordingly, a novel methodology based on the Bayesian Model Averaging (BMA) method was employed to combine predictions of three individual expert systems; Support Vector Regression (SVR), Generalized Regression Neural Networks (GRNNs), and Multi-layer Perceptron (MLP). The BMA model has the capacity to evaluate different model predictions and assign each one of them a weight on the basis of their performance. In this method, the MODELAVG toolbox with the MCMC-DREAM algorithm was used through the BMA models. With its ability to reflect the uncertainty of the estimation, this fusion-based approach represents improvements over former weighted-average techniques, such as straightforwardness, quickness and practicality (Vrugt, 2016, 2017).

To develop and verify the mentioned models, a comprehensive database of water levels and sediment depths utilized in this study were collected by the authors in Shiraz University's hydraulic lab from 18 distinct dam-break scenarios. Different initial upstream sediment depths which occupied 0% to 25% of the upstream reservoir's full depth of 300 mm and smooth or bumpy downstream as well as dry or wet downstream bed were considered. The experimental data were extracted directly from laboratory videos via image processing method.

Pertinent input data were divided into eight clusters on the basis of snap times after the dam breaks and then each cluster was split to train and test sets. In addition, several statistical modelling accuracy indices served to evaluate the efficiency of each expert system.

Based on statistical indices, the estimations of the proposed model were in close agreement with the measured data and had an appropriate performance in forecasting all water level and sediment depth data clusters with the MLP models marginally outperforming other expert systems, particularly in approximating data clusters. Considering statistical error indices values, the BMA model has offered superior performances compared to the best expert system in estimating most data clusters, signifying that the proposed methodology is explicit, straightforward, and promising for real-world applications.

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Keywords: *Computational intelligence systems, experimental data analysis, flash flood wave, Bayesian model averaging*

Risk assessment of groundwater vulnerability using machine learning

Masoumeh Zare [a], **Mohammad Reza Nikoo** [b], **and Amir H. Gandomi** [c]

[a] *Research Associate, Department of Civil and Architectural Engineering, Sultan Qaboos University, Muscat, Oman. Email: masoumezare86@gmail.com*
[b] *Associate professor, Department of Civil and Architectural Engineering, Sultan Qaboos University, Muscat, Oman. Email: m.reza@squ.edu.om*
[c] *Professor, Faculty of Engineering and Information Technology, University of Technology Sydney, Ultimo, NSW 2007, Australia. Email: gandomi@uts.edu.au*

Abstract: Due to rising population growth, overpumping from groundwater as one of the main sources of water supply has expanded. This overuse has led to increasing contamination concentration in these resources. In recent decades, the sustainable management and planning of water resources have facilitated the groundwater vulnerability index. Models are efficient tools to assess groundwater vulnerability, which perform better through optimizing according to the region's features, such as land use, playing a big role in the water resources pollution.

Accordingly, an index model with rating and weighting system is optimized. The model, considering anthropic factors, was derived from the DRASTIC model, the most common index model, namely DRASTICA. To modify the parameters rates, at first, the certain and uncertain parameters are determined via the one-parameter-at-a-time (OAT) sensitivity analysis. Then by applying the Wilcoxon method, as a rank-sum nonparametric statistical method, the rates are modified by means of the contamination concentration. Finally, the risk of uncertain parameters is considered accompanied by a non-dominated sorting genetic algorithms II (NSGA-II). The algorithm was developed according to four objectives, including minimizing the average value of transinformation entropy for the inverse of correlation between the model and contamination concentration and minimizing risk of the inverse correlation between the model and contamination concentration. The output is presented as a set of alternatives to non-dominated solutions. The best solutions are selected by a multi-criteria decision-making method (Rao and Lakshmi 2021; Aller 1985).

To compute the model, the initial hydrological and geological parameters of the models are obtained from the Regional Water Organization of Fars, Iran, for 30 observation wells throughout the Shiraz plain. Also, the land use is determined through verifying the provided land use map by the Natural Resources Organization of Fars, Iran, via Google Earth. The nitrate and sulphate concentrations in the observation wells are used to modify rates and optimize weights.

The vulnerability maps based on improved model show closer agreement with the nitrate and sulphate maps. Moreover, DRASTICA, because of using the additional parameter, performed better than the original model in assessing the vulnerability risk.

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Keywords: *Groundwater vulnerability index, DRASTICA, non-dominated sortinggenetic algorithm II (NSGA-II), multi criteria decision making (MCDM) methods, Wilcoxon test*

Characterising error in MODIS LAI products for eco-hydrological model calibration

Hui Zou [a], Lucy Marshall [a], Ashish Sharma [a] and Yating Tang [b]

[a] *UNSW Water Research Centre, School of Civil and Environmental Engineering, University of New South Wales, Sydney, 2052, Australia*
[b] *Department of Infrastructure Engineering, University of Melbourne, Victoria, 3010, Australia*
Email: lucy.marshall@unsw.edu.au

Abstract: Satellite remote sensing products, such as derived Leaf area index (LAI) are widely used to describe vegetation dynamics. However, compared to in-situ observations, satellite remote sensing LAI observation can suffer from large observational uncertainty. The accuracy of satellite LAI data is impacted by a range of error sources including antennae noise, structural uncertainty in surface backscatter (climatic, topographic and land cover conditions) and error in ancillary parameters required to parameterize retrieval models. Major overestimation of LAI occurs in some eastern Australian open forests and woodlands [1]. Ignoring the satellite LAI error will impair any model calibration using the data, for example in eco-hydrological models, resulting in overestimating model residual errors, and inaccurate estimates of parameters.

To address this problem, we use a new model calibration strategy and additional LAI error data products to decompose satellite LAI observation error from model residual error in model predictions, with the aim of improved model predictions. This approach, referred to as the Bayesian ecohydrological error model (BEEM) is firstly examined in a synthetic case to prove its validity, and then applied to two real catchments in Australia. Two additional LAI error data products, MCD15A2H product layer 'laiStdDev_1km', and layer 'FparLai_QC' are used to obtain the standard deviation of each LAI value and the class flags of the LAI observation quality respectively. BEEM [2] uses a novel likelihood function to describe the similarity between model predictions and real observations. The function works by dividing the total model error into a combination of observational error (estimated a priori) and residual error (inferred along with the model parameters). BEEM uses a Bayesian Adaptive Metropolis algorithm which sample parameters using an adaptive proposal distribution with covariance estimated from the history of sampled posterior parameters.

Results show that (1) the approach is valid in real and synthetic cases; (2) the approach improved LAI predictions and reduced model residual error for catchments when accounting for satellite LAI observational error. Our work shows the importance in fully utilizing the information from satellite products, considering the accuracy of satellite products is not always reliable. Further work should be to use ground-based observations to correct satellite products, to characterise the structure of the satellite LAI errors and to identify appropriate error models.

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***Keywords**:* *Satellite remote sensing, leaf area index, data error, uncertainty analysis*

Towards characterising a landscape-scale environmental digital twin: what for?, who for? and how?

Susan M Cuddy [a], **Matt Paget** [a], **Glenn Newnham** [a], **Martijn Mooji** [b], **David Lemon** [a] and **Peter Taylor** [b]

[a] *CSIRO Land and Water, Australia,* [b] *CSIRO Data61, Australia*
Email: susan.cuddy@csiro.au

Abstract: The term 'digital twins' (DTs) has been around since the early 2000s, mainly within the manufacturing, engineering and built environment sectors. But what is a digital twin in the context of the natural environment? What would/could it be used for, who would use it, and how might it be constructed? These are questions being asked by researchers/modellers of the 'natural' environment right now. The intention of this paper is to work through what a landscape-scale environmental digital twin (EDT) might be, using these 3 questions. The ultimate objective is to develop a EDT narrative that has meaning in the natural environment, has relevance to the spatial and temporal scales and data environments in which we work, and the questions we work to answer; and improves our ability to efficiently deliver our science.

While there are many definitions, typically based in the built environment of assets and infrastructures, the concept of a DT seems relatively easy to grasp – the dynamics of some physical artefact (e.g. a building, even a whole city) are replicated, synchronised and manipulated in a virtual world. The virtual 'twin' continuously (or regularly) learns from the physical artefact and vice versa. In this context, technologies that enable digital twinning include sophisticated data mining (machine learning) of large volumes of observed data routinely collected by in-situ (or remote) sensors and synthetic data created by simulation models, driven by artificial intelligence techniques that turn the data into information using virtual and augmented reality viewers. Advances in these technologies serve to accelerate the development of DTs. An Australian example is the 4D (3D plus time) Digital Twin NSW – integrating NSW's spatial data with live transport feeds, infrastructure building models, and much more. Another example is Sydney Water's 10-year program to build multiple, integrated digital twins of their assets, with the aim of increasing efficiency in their asset management decisions.

In the natural environment, purpose and use (i.e. the 'what for') and the 'who far' are less clear, with few implementations to learn from. Starting with specific use cases – e.g. 'to maximise benefits from environmental watering actions, at basin scale' – may not be helpful as there will be a temptation to tune applications to support the specific use case and compromise support for others. In an industrial setting, the costs associated with building DTs are offset by efficiencies gained for the organisation. So, realising efficiencies is an important 'what for', tightly coupled to 'who for'? For researchers and practitioners, it may be that reducing inefficiencies in the lifecycles of data and code, from creation through to deployment/archive, is enough reason. Other 'what fors' could be 'to do things we are not able to do otherwise' or 'to design and test scenarios that integrate change processes (climate, population growth, catastrophes) and their likely implications for interventions'. Even 'changing the way we do science' has been proposed. As with the data and code candidates, these are tightly coupled to the 'who for'.

Finally, the 'how', i.e. the hard and soft technologies, protocols and practices, necessary to realise the 'what fors' – an EDT is going to look very different from the built environment examples, driven by different purposes, uses, and ultimately funding arrangements. For example, while built environment data streams are dense, environmental data streams are relatively sparse (in time and place) and multi-sourced. FAIR (findable, accessible, interoperable, reusable) data is at the heart of DTs and surely an essential characteristic for an EDT. FAIR code (packaged in some agreed way) is another, as are protocols and methods to integrate/assimilate many and disparate data for understanding system state; and the ability to model interdependent processes.

In conclusion, now is the time to translate the significant (and growing) investment in DTs in the built environment into the natural environment modelling domain. Whatever an EDT is – and our understanding of this will mature over time – to realise return on investment it must be attractive, relevant and accessible to many in the modelling and simulation community, and not confined to high-end technology specialists.

Keywords: *Digital twin ecosystem, Digital twin reference framework, FAIR data, Big Data analytics*

Enabling integrated modelling systems for environmental prediction at national scale

A. Specht [a], S.M. Guru [a] and B. Morris [a]

[a] *Terrestrial Ecosystem Research Network (TERN), University of Queensland.*
email: a.specht@uq.edu.au

Abstract: As clearly established in a series of discussion papers commissioned by the Australian government, there is an urgent need for improved ability to integrate the wealth of available data and modelling expertise to enable flexible and timely prediction of future environmental scenarios. The Australian government, under the National Collaborative Research Infrastructure Strategy (NCRIS), has established a robust research infrastructure[1] for the organisation of data and information across many environmental domains. This has enabled unprecedented access to systematically collected and curated high-quality data. As a result, some limited, largely domain-specific predictive capacity has developed, but active and continuing cross-domain synthesis is required for effective responses to the multi- and trans-disciplinary challenges facing us, such as the threats posed by climate change and other environmental hazards associated with breaching our planetary health boundaries.

In this paper we present an approach to establish a cross-domain, cross-institution environmental prediction capacity. This structure is designed to provide the opportunity for (i) exploration and further insight into key cross-domain processes, (ii) a transdisciplinary work environment for participatory modelling, (iii) and the continual development and provision of tools across the whole decision-making workflow, resulting in (iv) outputs that are defensible and reproducible. By employing an adaptive approach, the proposed infrastructure will be responsive to technological and environmental changes and imperatives in the long term.

The framework proposed is informed by several federations around the globe including the National Centers for Environmental Prediction in the USA and the UK Environmental Prediction research project. The capability we are proposing for Australia is broader in scope than these, which are focused on particular areas of concern, such as risk from extreme weather events. There is growing impetus to develop such capabilities for broader environmental and ecological prediction, for example through the Ecological Forecasting Initiative in the USA, where NEON data are being leveraged to better assess short-term forecasting for ecological systems. We propose a framework that (i) will leverage the data from the NCRIS facilities so it can easily be incorporated into modelling systems, (ii) will provide an in-house, curated modelling capacity, and (iii) provide validation and visualisation opportunities to best enable predictions. These components will be coupled with a structure to support collaborative work with the wider research and policy-making communities not only to ensure there is effective, high quality inter- and trans-disciplinary input on subjects of concern, but to ensure relevant participatory modelling is facilitated, and model validation is active and open. Informed by such collaboration, relevant decision support tools will be accessed and made available to quickly test predictions about the effects of events such as wildfire.

We argue that six components need to be in place, interlocked and interdependent for the development of a responsive and adaptive framework:

1. readily available, high quality multi-domain data;
2. relevant data harmonised and scaled while ensuring provenance, vocabularies and workflows are properly described, registered and reproducible, ready for complex modelling;
3. a shared platform for the creation, harnessing and modification of models by users;
4. strong coordination with the wider community using an adaptive co-learning and co-design approach;
5. translation tools for model testing and communication of outcomes; and
6. social and technical governance structures to transparently manage and coordinate the overall program and the infrastructure.

Our aim is to ensure adherence to the FAIR principles for research, and where possible, the outputs will be openly accessible and re-usable. Although in the first instance we expect the framework will be largely used by researchers in government and academia, we envision, once it is established, it will be available to other users on a cost-recovery basis.

[1]where 'Research infrastructure' includes the physical facilities, human resources and related services that are used by the research community to conduct research' (Research Infrastructure Review Final Report September 2015, https://bit.ly/2WAPczc, accessed 17 August 2021)

Keywords: *Environmental prediction, framework, digital infrastructure, modelling, Data as a Service*

EXTENDED ABSTRACT ONLY

DAESim: A Dynamic Agro-Ecosystem Simulation Model

Firouzeh Taghikhah [a] **, Justin Borvitz** [b]**, Robert Costanza** [a]**, and Alexey Voinov** [c]

[a] *Crawford School of Public Policy, Australian National University, Australia*
[b] *Research School of Biology, Australian National University, Australia*
[c] *University of Twente, Netherlands*
Email:Firouzeh.th@gmail.com;

Abstract: In a world of increasing population, changing climate, and decreasing availability of arable land, there is an urgent need to preserve and improve the quality of our agricultural ecosystems. Agriculture in Australia has always been vulnerable to extreme weather patterns and other environmental hazards. As such, risk and resilience are crucial factors in managing its social-ecological farming systems. With mounting pressures of climate variability, threats to sustainable food production increase in frequency and intensity, constituting significant risks to farmers, consumers, and the financial and policy institutions supporting these systems. Such risks are a strong incentive for the joint development of methods directed at their integrated analysis and prediction. Better-informed farm management procedures based on integrated modeling would reduce risk while enhancing structural resilience and long-term wellbeing. To better understand and forecast alternative futures for agricultural production, we have developed a dynamic simulation model named DAESIM. Our proposed integrated model is intended to be extensive in its reach, combining analysis of the economic aspects of risk with climate-based yield stability forecasts. It encompasses the environmental and social capital considerations underlying individual and societal wellbeing. The model outputs are valuable to farmers, land managers, and policymakers seeking to support the agricultural sector. To date, financial institutions have not supported farming methodologies that prioritize values other than short-term profit – this has suppressed the development of integrated farming models with long time horizons. The banking sector relies overwhelmingly on conventional mechanisms that do not account for social and environmental worth. Intended outcomes of the proposed research would include the amendment of policy to reward, or at the very least not punish, farmers who adopt long-term approaches. For farmers seeking to build resilience against environmental hazards, establishing a firm causal connection between natural capital and financial performance can justify trade-offs against immediate profit and provide financial and government institutions with the means to value and manage those decisions.

Keywords: *Integrated modelling, carbon sequestration, regenerative agriculture*

Application of a delayed logistic equation to a reindeer population in a closed environment

S. Watt [a] and Z. Jovanoski [a] and I. Towers [a] and R. Saifuddin [b] and H. Sidhu [a]

[a] *School of Science, UNSW Canberra, PO Box 7916 Canberra BC, ACT 2610, Australia*
[b] *Department of Cyber Security and Games, Canberra Institute of Technology, 37 Constitution Ave, Reid ACT 2601, Australia*

Email: simon.watt@adfa.edu.au

Abstract: Reindeer are not an invasive species by nature. However, introducing reindeer into a pristine environment with an abundance of lichen, the reindeer's favourite food, can have a devastating effect on the local environment if the herd population is not managed. This is mostly due to the slow lichen regrowth, decreasing the carrying capacity due to resource depletion. In these circumstances, a non-invasive species, like reindeer, can be considered as an invasive species whose actions threaten its own survival, because of its over utilisation of native resources.

We consider a population of reindeer, which were introduced in 1911 to St. George Island (one of the Pribilov Islands of the coast of Alaska). This was seen as an outdoor laboratory, with the population observed for forty years. As there was little hunting pressure on the herd and with no natural predators, this is considered as an almost closed system. The reindeer population grew almost exponentially in the early years of their being introduced, then started to decline, and eventually died out due to the lack of available resources; lichen reserves were exhausted over a 40 year period. Small amplitude oscillations in the reindeer population of St. George Island was noticed. Stable oscillatory behaviour is often observed experimentally. We hypothesise that these oscillations are due to the combined effects of gestation and maturation.

Accordingly, a single-species population growth model with a variable carrying-capacity is considered. The carrying-capacity is treated as a state-variable, representing the availability of a non-renewable resource (the lichen). We investigate a model based on the logistic equation where the rate of decrease of the carrying-capacity is proportional to the size of the population. We apply this model, with and without constant time-delays, to the reindeer population of St. George Island. The model that best fits the data includes a delay in the population and in the carrying-capacity. The estimated delay of 2.062 years coincides with the combined length of gestation and herd maturation.

Keywords: *Population modelling, invasive species, delayed differential equations*

The population dynamics of ecosystem engineers and habitat modification

S. Watt [a] **and Z. Jovanoski** [a] **and I. Towers** [a] **and R. Saifuddin** [b] **and H. Sidhu** [a]

[a]*School of Science, UNSW Canberra, PO Box 7916 Canberra BC, ACT 2610, Australia*
[b]*Department of Cyber Security and Games, Canberra Institute of Technology, 37 Constitution Ave, Reid ACT 2601, Australia*
Email: simon.watt@adfa.edu.au

Abstract: We consider a native species whose environment is stressed due to the presence of an ecosystem engineer, a specific type of invasive species that has the ability to convert native habitat into one which is more conducive to its own survival. The re-engineering of the native habitat results in an increase in the intra-species competition among the resident species. A key aspect of ecosystem engineer dynamics is that their invasion is limited by the size of the native habitat and their ability to transform it. It has long been recognised that invasive species play a role in declining biodiversity and the degradation of native habitat.

We explore the effect of a single engineer species on a resident species and its habitat. The invading engineer species does not prey on the resident species but does compete for available habitat. The engineer species converts, modifies or re-engineers native habitat. The rate at which this conversion is performed determines whether or not colonisation will be successful. Over time the converted habitat degrades forming a decayed habitat that is not suitable to either species. The decayed habitat returns to its native state through a process of recovery. Once in its native state the habitat can be occupied by either the resident species or modified again by the ecosystem engineer. This recycling of the habitat is an important and novel feature in the model.

We investigate the dynamics of this model. We assume the dynamics of both species is governed by a logistic-type differential equation whose carrying capacity is equal to the size of its habitat. In the logistic equation, it is the carrying capacity that determines the population size. A reduction in habitat will drive the population to a smaller size, similarly an increase in habitat will increase the population size.

An analysis of the model reveals three different approaches that may be used to control the invading species. The first is based on reducing the ability for the engineer species to convert native habitat. The model shows the existence of a minimum conversion rate below which the engineer species can not colonise the native habitat. Therefore conservation strategies should focus on reducing the engineer's ability to convert habitat. A second strategy is a well known strategy, the harvesting of the invading species. And the third is based on 'quarantining' the decayed habitat for a certain period of time. Although quarantining does not alter the conversion rate it does however favour the resident species by not permitting the engineer species to become the dominant species. However, large quarantine periods cause oscillations within the system which may not be desirable.

Finally, we propose directions for future work.

Keywords: *Population modelling, invasive species, mathematical modelling, harvesting*

A framework for engaging stakeholders in solving real-world water resources management problems

W. Wu [a], H. R. Maier [b], G. C. Dandy [b], R. Leonard [c], K. Bellette [d], S. M. Cuddy [e] and S. Maheepala [f]

[a] Department of Infrastructure Engineering, The University of Melbourne, Melbourne, VIC, [b] School of Civil, Environmental and Mining Engineering, The University of Adelaide, Adelaide, SA, [c] Translational Health Research Institute, Western Sydney University, Sydney, NSW, [d] Environment Protection Authority, Adelaide, SA [e] CSIRO Land and Water, Canberra, ACT, [f] Department of Environment, Land, Water and Planning, Melbourne, VIC.
Email: graeme.dandy@adelaide.edu.au

Abstract: Multi-objective evolutionary algorithms (MOEAs) are becoming increasingly popular for solving environmental and water resources optimisation problems. In the past, the focus of these studies has generally been on methodological issues related to the optimisation algorithm, while the incorporation of stakeholder preferences in the MOEA solution process has largely been ignored. In recent years, there has been increased recognition of the need to apply these approaches to real-world problems to facilitate the realisation of their full potential. However, in most of these studies, stakeholder input was only used to direct the optimisation search process or select the final optimal solution(s), while the contribution of stakeholder input to other important components of the problem solving process was not considered. The reason for this is that the full consideration of stakeholder input in solving environmental and water resources optimisation problems requires the development of a more holistic approach, which involves a range of additional challenges.

To address these challenges, a framework for including stakeholder input in real-world optimisation problems has been developed as part of the Optimal Water Resources Mix (OWRM) project initiated by the South Australian Government through the Goyder Institute for Water Research. The framework includes a conceptual framework (Figure 1) and a procedure for its implementation. The framework was applied to an urban water supply security study for Adelaide, South Australia. A summary of the framework and how it was implemented to identify optimal water sourcing options for the Adelaide case study is presented in this paper.

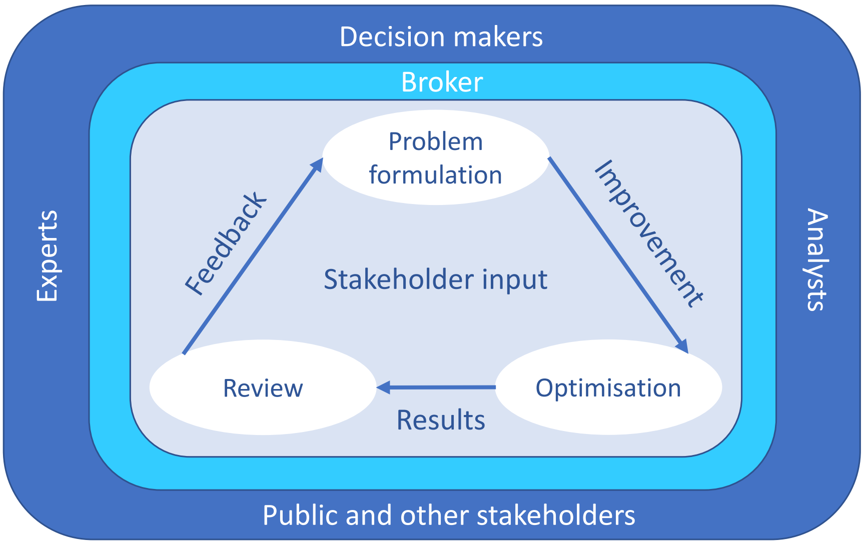

Figure 1. The proposed conceptual framework. Adapted from Wu et al. (2016)

This study highlights the important role of stakeholder input at the various stages of the problem formulation and optimisation process, analysis and results, although it can be expensive and time consuming to do so. It is recommended that adequate resources be made available for stakeholder engagement in project plans and budgets, as there needs to be clear and ongoing communication between stakeholder groups throughout the project. It also demonstrates that the use of MOEAs as the optimisation engine, together with appropriate stakeholder input, provides a combination that is well-suited to solving real-world water resources problems.

Keywords: *Integrated urban water management, Multiobjective optimisation, Stakeholder preferences*

Application of topic modelling to Integrated Water Resource Assessment domain

M.G. Erechtchoukova [a], **A.K. Kohli** [a]

[a] *School of Information Technology, Faculty of Liberal Arts and Professional Studies, York University, Canada*

Email: marina@yorku.ca

Abstract: Integrated Water Resource Assessment (IWRA) is a multidisciplinary analysis of cause-effect interactions of environmental, social, and economic processes which play an important role in an investigated scenario or undertaking related to a water resource. The goal of this analysis is to generate new knowledge in support of decision or policy making. The concept of IWRA covering natural processes in a water resource with at least one of the areas of economic or social aspects of modern society had been articulated almost a half a century ago. Nowadays, it became mature to the extent of supporting environmental sustainability and promoting UN Sustainable Development Goals through offering well-accepted approaches, frameworks, simulation models and computational techniques upholding the assessment. Nevertheless, there is steady interest to the issues of IWRA among researchers and practitioners because new technologies open opportunities for advanced computational techniques and comprehensive analysis. This study presents exploratory analysis of the corpus of scientific publications using text mining techniques with the aim to identify salient topics and potential gaps in the IWRA research area. The analysis was conducted based on the topic modelling approach. Topic modelling is a form of text mining that allows to find a representation of information from a collection of documents called corpus. Any text document can be viewed as a collection of several themes which are present in the document and reflect the document contents in a meaningful to its readers way. A theme or a topic is represented via an array of words that have a high tendency of co-occurrence when a particular theme underlying a document is being discussed. The most salient characteristic of topic models is that they automate the process of extracting these underlying (latent) themes in large corpora of texts without any human intervention excluding text pre-processing. Given that a topic model operates with a fixed vocabulary, domain specific analysis is expected to be more informative. Therefore, careful selection of documents included into a corpus is required. Application of topic modelling to multidisciplinary areas such as IWRA carries more importance because it helps to automate the process of extraction of salient topics relevant to a document and categorize the documents into themes for targeted analysis and knowledge extraction. The corpus of abstracts of 89726 papers published from 1970 to 2020 in peer-reviewed journals representing leading outlets in the areas of water resources and integrated environmental assessment was assembled. It was analysed using basic bibliometric statistics. After that, the corpus was pre-processed following conventional topic modelling framework and fed into LDA mallet algorithm to identify salient topics. Hyperparameters of the selected topic modelling algorithm were identified based on exploratory computations and evaluation of several topic models performance using a coherence score and qualitative evaluation of the identified topics. The model producing 20 topics was considered satisficing and used as a basis for the qualitative analysis of clusters of words forming topics. The analysis revealed two categories of latent topics presented in the corpus: methodological and environmental. The latter describes various aspects of utilization, protection, and restoration of a natural water resources. No theme reflecting assessment of socio-economic processes was uncovered despite the fact, that these processes play critical role in the environmental state of a water resource.

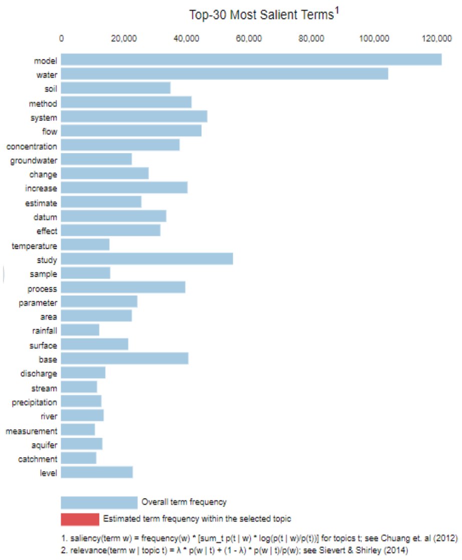

Figure 1. Top 30 salient terms

Keywords: *Topic modelling, LDA mallet algorithm, Integrated Water Resource Assessment, text mining*

An ML-based study of extreme weather events incorporating seasonality factor

Peter Khaiter [a] and **Masooma Suleman** [b]

[a] *School of Information Technology, York University, Toronto ON, Canada,* [b] *School of Computer Science and Engineering, Vellore Institute of Technology, Chennai, India*

Email: masooma20suleman@gmail.com

Abstract: It has been recognized that one of the most visible manifestations of global climate change is an increase in the intensity and frequency of extreme weather events. The latter include droughts, heat waves, heavy downpours, tornados, typhoons, and major hurricanes. In this paper, we propose a conceptual framework for assessing extreme weather conditions incorporating the factor of seasonality. The study was based on historical meteorological data of Ahmedabad city, India (latitude: 22.9914, longitude: 72.6167) consisting of daily average temperature (°C), minimum temperature (°C), maximum temperature (°C), wind speed (m/s), surface pressure (kPa) and precipitation (mm) collected over the past 38 years, from 1st January 1982 to 31st December 2020 (Figure 1).

Figure 1. Location of the study area (city of Ahmedabad in India).

The main steps of the framework are shown in Figure 2. We used boxplot technique to visualize the dataset and determine the central tendency, range, symmetry, and the presence of outliers in data. Predicting extreme weather events based on fixed seasonal time frames may produce inaccurate or biased results. It is important to consider the seasonal variability across the years before detecting extreme weather events and predicting their trends. We conducted cluster analysis to group observed data points into distinct seasons based on the similarity in their meteorological features. Given an obvious time-oriented nature of data, K-means clustering algorithm with dynamic time warping metric to measure similarity have been applied. The resultant clusters (i.e., artificial seasons) have been used to study the variation in seasonality across contiguous years and to identify the long-term trends in extreme weather conditions (namely, temperature and precipitation) within a seasonal context over a 38-year period (1982-2020). Traditionally, the study of extreme weather events includes computation of 5th, 10th, 90th and 95th percentiles of observed meteorological data as thresholds across the time periods, and this approach is extensively applied and recommended in the literature. However, in the prior research, the thresholds have been computed across the whole periods, whereas we used these thresholds and computed them over derived seasonal clusters to analyze the extreme weather events pertaining to a given season. Additionally, we included 1st and 99th percentile thresholds as severe/extreme weather events. The magnitude trends in extreme hot and extreme cold events during each season and extreme rainfall events in the "Monsoon" season have been estimated and visualized.

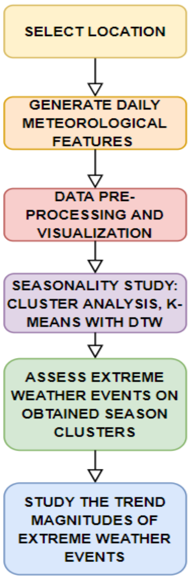

Figure 2. The proposed conceptual framework for studying seasonality and extreme weather events factoring seasonality.

It would be worthwhile to include the intensity of precipitation and humidity for a finer determination of seasonality. In combination, we can analyse the contribution of each meteorological feature to the formation of clusters (seasons) and compare our obtained results with different permutation of features in K-means.

Keywords: *Unsupervised learning, extreme weather event, dynamic time warping, seasonal clustering*

EXTENDED ABSTRACT ONLY

Data analytics approach to climate change studies

P. Khaiter [a] and **E. Bhardwaj** [a]

[a] *School of Information Technology, York University, Toronto, Canada*
Email: eshtab@my.yorku.ca

Abstract: The observed trends of climate changes produce a wide range of effects to the sustainability of normal lifestyles, and there are good reasons to believe that this tendency will continue and even aggravate in the future. The application of data analysis techniques can increase the public awareness about climate change problems and studies while introducing additional research methods and results. The proposed research is aimed to formulate a novel data analytics framework for climate change studies to address the gap in data modelling in the domain by creating standardized guidelines for collecting, extracting, preparing, and visualizing the climate data. The research problem of particular interest is to compare data projected by the climate models against observed data for a common period to assess the accuracy of modelling predictions. A practical implementation of the framework is a visualization tool aiding researchers and practitioners in their analysis of climate data. The multidisciplinary nature of this work lies in the combination of information technologies, data analytics, climatology, and data visualization to create a standardized roadmap for data analytics in the domain of climate studies.

The data analysis methodology for climate change studies applied in this work uses the common scheme of a standard data analytics structure with the following conventional steps:

1. Data collection and extraction
2. Data wrangling
3. Implementation/visualization

However, the tasks within each phase address the complexities and specific features imposed by the climate change domain. The intricacies of Phases 1 and 2 are mainly targeting the challenge of automating and standardizing each task in the process. The raw format of the datasets is progressively transformed to the form of easily accessible and readable csv files which showcase the projected and observed values of climate variables for each calendar date within one record. This configuration of data is an ideal model which can be recommended for similar studies analyzing climate data.

Furthermore, the visualization tool facilitates a broad variety of possible climactic considerations. Users can choose from eight climate variables to visualize a daily comparison between the values of climate parameters projected by the model and those observed for a period of up to 15 years (see a one-year example in Figure 1). In addition, users have the ability to download the corresponding graphs and data to perform their own studies.

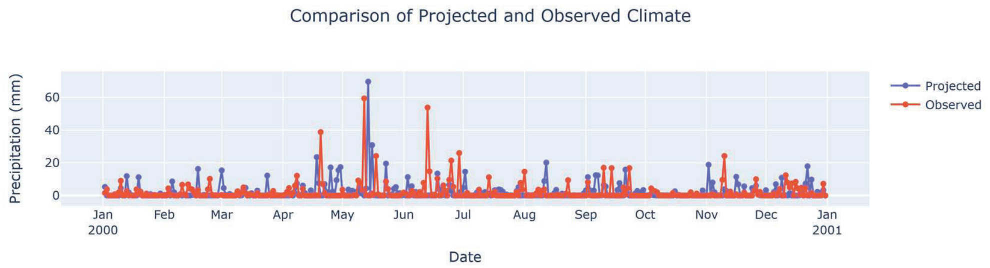

Figure 1. Sample output from visualization tool for daily precipitations (liquid water equivalent) in 2000.

The data analysis and visualization framework presented in this study addresses the lack of data pipelines to pre-process, analyze, and model climate data. This guideline for standardization allows wider research methods to be developed aiming at investigation and prediction of impending climate changes and their impacts. Lastly, regional climate analysis can be given greater consideration and focus with the knowledge gleaned from comparison tools of this kind.

Keywords: *Climate change, data analysis, visualization tool, climate model*

Improving seafood production through data science methods

P. Khaiter [a], **B. Teimouri Lotfabadi** [a]

[a] *School of Information Technology, York University, Toronto, Canada*
Email: teimoori.bahareh@gmail.com

Abstract: Global production of seafood has quadrupled over the past 50 years. Seafood production is characterized by one of the highest waste rates in the food industry reaching up to 50% of the original raw material which is obviously not only one of the serious challenges for the sector due to the tangible economic losses being incurred but also a serious negative impact on the environmental conditions (Arvanitoyannis et al. 2008). Therefore, seafood companies are interested in reducing their waste rates, thus increasing production yields. In this study, a Data Science (DS) approach has been applied as a methodological foundation to a broad spectrum of theoretical and practical issues in the seafood production industry. Based on this approach, we suggested and elaborated a DS framework, phases in its development lifecycle and a common roadmap to be followed in the future projects in the domain. The framework encapsulates data processing, statistical, machine learning, optimization, and visualization capabilities. The research employs unique real-world data collected in a seafood production facility over a 2-year period.

The framework, as shown in Figure 1, starts with data collection on each technological stage, spanning from catching the raw Tuna fish all the way through to the final production of Tuna cans, followed by accessing and extracting corresponding datasets from the databases accumulated by the industry companies. On the next step of the framework, necessary Data Preprocessing and Data Cleansing procedures are to be performed preparing data for Statistical Analysis aimed at a better understanding of the underlying relationships between features and deriving useful insights, such as correlations between features and their distribution patterns. Feature Engineering and Extraction phase is meant to arrange the dataset for the modeling stage. Investigation of performance abilities of various Machine Learning algorithms and selection of the best predictive model is the next step of the framework. To complete the scope of the framework, an optimization phase embeds the best performing model and optimizes for the best set of raw material and process control parameters resulting in highest production yield. The optimization module of the DS framework as well as perspectives of its implementation and deployment are discussed in the presentation.

Figure 1. Detailed Roadmap of the DS Framework.

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Keywords: *Seafood production, waste rate, production yield, data science, machine learning*

Data-driven approaches to rainfall nowcasting for application in hydrological modelling

Rim Mhedhbi [a], **Marina G. Erechtchoukova** [a]

[a] *School of Information Technology, York University, Toronto, Canada (rimouch1@yorku.ca)*

Abstract: Flash floods are amongst the most complex and destructive phenomena. An abundance of process-based and data-driven models was proposed to serve as decision support tools for flood management authorities. While various observed hydrological and meteorological characteristics were usually used as an input for flash flood modelling, it was also found that integrating rainfall forecasts could considerably enhance the models' predictive ability. This study focuses on finding reliable and efficient data-driven rainfall nowcasting models (0-2h lead time). These models could then be integrated into a short-term flash flood prediction framework to investigate the framework performance including the effect of the precipitation nowcasts on the reliability of the modelling results. It is important to note that only data from rain gauges located on the same watershed are used to predict future precipitation. Rainfall data obtained from two rain gauges installed in the Spring Creek watershed, Ontario, Canada were used in this study. The investigated watershed is highly urbanized and prone to flash floods. Investigated data spanned four years from 2013 to 2016. We tackled this data-driven modelling problem from two perspectives: (1) an algorithmic and (2) a data-centric. From the algorithmic perspective, a comparative study of three data-driven models was performed. These models included the status quo persistence model, the statistical AutoRegressive Integrated Moving Average (ARIMA) model and the deep learning Long Short-Term Memory (LSTM) model. These models were applied to each time series to predict rainfall in the respective rain gauge location (univariate modelling). Following the data-centric approach, data from both sensors were combined into one dataset to predict rainfall in each sensor location (multivariate modelling). Lagged rainfall values from the sensor at the target location and the adjacent sensor were fed into an LSTM model to predict rainfall at the target location. Models were created for each investigated year for lead times ranging from 15 minutes to 60 minutes (corresponding to the time scale of the investigated rainfall events). Data for each year were chronologically split into training and testing with a 70%:30% split ratio. Root Mean Square Error (RMSE) and Maximum Residual Error (MRE) were used as evaluation metrics. Obtained results showed that overall, according to the estimated RMSE, LSTM demonstrated a better performance for all years except the year 2015. Figure 1 depicts models' performance for 2013 at the Hart Lake location using single sensor data. Further analysis revealed that the year 2015 had major hydrological pattern difference between the training and testing sets. MRE did not indicate major variations between the years; it was found that all the models performed approximately at the same level as the persistence model. The models failed to predict extreme values accurately. The data-centric approach, however, showed different results. According to the RMSE and MRE metrics, LSTM models trained using data from both sensors demonstrated major improvement on data from years 2014 and 2015 for both target areas. Evaluation of the model performance on data from years 2013 and 2016 gave inconsistent results. Further investigation showed that the improvement in the model predictive ability coincided with the sensors' location and the dominating wind direction in the modeled years. In general, combining data from multiple sensors when used with the LSTM model showed promising results. Further extension of input variables including meteorological data collected on the investigated watershed will be the next step of the presented study.

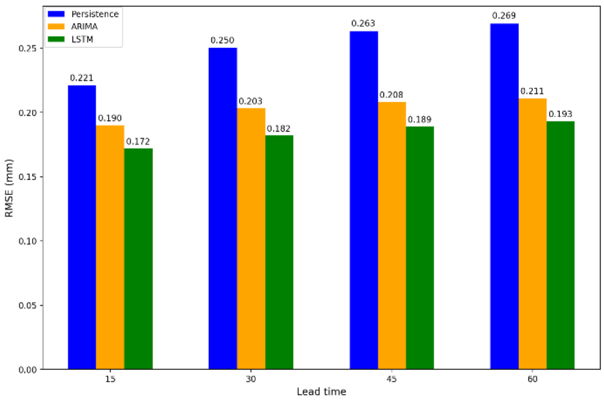

Figure 1. Models performance in terms of RMSE on Heart Lake location 2013 data.

Keywords: *Rainfall nowcasting, data-driven modelling, LSTM, ARIMA, precipitation*

Lessons learned using dSedNet plug-in within a water supply catchment for Greater Sydney

Suraya Amini[a], **Jordan Pont**[a], **Marlène van der Sterren**[a] **and Andrew Freebairn**[b]

[a] *WaterNSW, Sydney Australia*
[b] *CSIRO,Canberra*
Email: marlene.vandersterren@waternsw.com.au

Abstract: Previous studies have identified that water quality in lakes and reservoirs can be closely associated with the hydrologic regime of flood and drought events. Extended low flow events can change the driving mechanisms of water quality constituents, particularly sediment loads, due to increased residence times and reduction in flushing. WaterNSW is developing a catchment to supply water quality and quantity model for the Greater Sydney supply system. The modelling of sediment within the water column and runoff profile is deemed critical to manage good quality water supplies.

Key drivers of total suspended solids within the water column are hill slope, gully and stream erosion. These processes are further exacerbated by a lack of ground cover post bush fire in WaterNSW's heavily forested catchments. This paper explores the use of the CSIRO dSedNet plugin in the eWater Source program and the challenges faced adopting them in the Warragamba and Avon catchment models.

This study highlights the importance of setting up modelling files within the right context and ensuring data integrity throughout the spatial data. WaterNSW worked with CSIRO to update the help files and documentation to assist others in taking up more detailed sediment modelling within catchments.

Keywords: *Sediment, modelling, Source, SedNet plugin*

Digital platforms deliver rapid assessments of Australian mega-fires on two bird species

Robert S. Clemens[1], Shawn W. Laffan[2], Sama Low-Choy[3,4], Brendan G. Mackey[5] Kristen J. Williams[6], and Jenna Wraith[1]

[1]EcoCommons Australia, Nathan Campus, Griffith University
[2] School of Biological, Earth and Environmental Sciences, The University of New South Wales, Sydney 2052
[3]Centre for Planetary Health & Food Security, Nathan Campus, Griffith University
[4]Griffith Institute of Educational Research, Mt Gravatt Campus, Griffith University
[5]Climate Action Beacon, Griffith University Griffith Sciences, Gold Coast Campus, Griffith University
[6]CSIRO Land and Water, GPO Box 1700, Canberra, ACT, 2601, Australia
Email: shawn.laffan@unsw.edu.au

Abstract: As vast quantities of data become increasingly available there are growing opportunities to find and use these data in appropriate ways to better understand our changing world. Digital platforms are increasingly facilitating rapid access to growing datasets while providing computational tools which optimise the use of those data. The Biodiversity and Climate Change Virtual Laboratory (BCCVL) and ecocloud are providing that functionality to ecological modelling.

Fires during the summer of 2019 – 2020 scorched more than 18 million hectares of eastern Australian forests. These fires had unprecedented impacts on wildlife, but immediately after the fires, the magnitude of the impacts on each species was unclear. Here we show how the functionality within BCCVL can deliver these kinds of assessments rapidly by generating species distribution models for the Greater Sooty Owl and the Superb Lyrebird. We then compare our results to independent studies (Ward et al. 2020). We further demonstrate the utility of the kinds of new datasets becoming available by showing the benefit of adding a Habitat Condition Assessment System (HCAS) derived environmental variable (Williams et al. 2020) to these analyses.

We modelled species distributions using four modelling approaches available within BCCVL: Maxent, Boosted Regression Trees, Generalised Linear Models and Artificial Neural Networks. Resulting predictions were then overlaid by a map of the 2019-2020 south-eastern Australia megafires (Mackey et al. 2021). When we compared results. the percentage of predicted suitable habitat that was impacted by fire was very similar in our modelling to the results generated by other experts and researchers. In BCCVL, the best models were generated using Maxent with the inclusion of the HCAS data.

The total area of suitable habitat in our modelling varied substantially depending on the algorithms and data used. This was most pronounced in Greater Sooty Owl predictions. This indicates that as more habitat was predicted as suitable, the proportions of that habitat, which was either burned or unburned remained constant, a reflection of the huge scale of these fires. The tools available in BCCVL and ecocloud provide similar results to other investigations but do so more rapidly and are much more broadly accessible. Accessibility and usability of these tools will be further improved when they are migrated to the EcoCommons platform.

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Keywords: *Digital platforms, species distribution models, bushfires*

Is Sydney really a 30-minute city? Using a door-to-door approach to evaluate policy aspirations

Lauren Del Rosario[a], Shawn W. Laffan[a], Eve Slavich[b] and Christopher J. Pettit[c]

[a] School of Biological, Earth and Environmental Sciences, University of New South Wales, Sydney, 2052, Australia, [b] Stats Central, Mark Wainwright Analytical Centre, University of New South Wales, Sydney, NSW, Australia, 2052, [c] City Futures Research Centre, School of Built Environment, University of New South Wales, Sydney, NSW 2052, Australia
Email: l.coyle@unsw.edu.au

Abstract: The 30-minute city promises average commuting times of one hour per person per day and is a key part of both the Metropolitan planning strategy for Sydney and the Smart Cities Plan for Australia. However, existing calculations of the 30-minute city do not include the first-mile and/or last-mile segments of public transport journeys. These calculations often misclassify true commute times and, if used to inform planning policies, existing inequalities may be entrenched. This research uses trip planner API data and a synthetic population matched with smart card data to estimate door-to-door public transport travel times. The algorithm is used to measure how effectively the goal of the 30-minute city is met in Sydney in terms of door-to-door travel times compared to calculations that do not include first-miles and last-miles. 62.0% of synthetic commuters were modelled to have public transport commutes of 30 minutes or less for the journey to work without first-miles and last-miles, which would support the notion that Sydney is a 30-minute city on average. However, only 21.7% of synthetic commuters had door-to-door commutes modelled as 30 minutes or less. Only 7.2% of Statistical Area Level 1 (SA1) small areas were modelled as having average door-to-door public transport commutes that were 30 minutes or less. However, this figure was overestimated at 33.0% of SA1s when first-miles and last-miles were not included. Such substantial differences in estimates of accessibility could influence different policy and infrastructure outcomes. A door-to-door approach should be used to underpin future metropolitan planning policies. This approach shows that the 30-minute city goal for public transport commutes is yet to be realised in Sydney.

Keywords: *Big data, synthetic population, smart card, travel time, door-to-door*

Simulating land use change in a long-term SSP2-4.5 scenario simulation to support regional landscape planning and policy design

Sonja Holler [a,b], **Melvin Lippe** [a], **Olaf Conrad** [b], **Daniel Kübler** [a], **Jürgen Böhner** [b] **and Sven Günter** [a]

[a] *Thünen Institute of International Forestry and Forest Economics, 21031 Hamburg, Germany*
[b] *Universität Hamburg, Center for Earth System Research and Sustainability (CEN), 20146 Hamburg, Germany*
Email: sonja.holler@thuenen.de

Abstract: The long-term future impact of land use change on forest landscapes and its consequences for restoration require simulation approaches that incorporate the increasing uncertainty of climate change, acknowledge long-term changes in population density, settlement expansion, and the related demands for land resources.

We present an innovative forward oriented long-term scenario land use modelling tool that approaches the dichotomy of a flood of data and data-limiting situations. The cellular automata model includes probabilistic functionality and simulates annually the theoretical maximum anthropogenic impact and available restoration area potential during the period of 2018 to 2100 for smallholder dominated landscape configurations.

The model bases on the open-source PLUC (PCRaster Land Use Change) model based on the PCRaster Python framework that embeds map algebra and other spatial operators (Verstegen et al., 2012). A series of model algorithm innovations were implemented to depict scenario development regionally within the hectare-scale and derive future forest status information with the available input data.

Objectives for model development were (1) to assess the potential long-term impact of smallholder-driven land use change exemplified for a sub-national regional forest landscape area in Ecuador (> 1.6 million pixels) under the assumptions of a SSP2-4.5 baseline scenario, (2) to derive the probable impact of two forest policy guideline scenarios, (3) to depict the potential impact on and of remaining forest, and (4) to determine the most probable landscape configuration under those assumptions as well as derived a possible landscape configuration under a restoration paradigm in comparison. The model is highly flexible in its code-design to depict varying scenarios by changing input maps and parameter settings. Global, national and regional primary and secondary data (time series and cross-sectional survey data among others) were combined, and middle of the road scenario assumptions implemented in the model.

Information of the SSP2-4.5 scenario (dynamic development of population and their demand, dynamic settlements, climate change impact on potential forest distribution and above-ground biomass production per projected climate period) is computed in a spatially-explicit and deterministic fashion. The uncertainty of human behavior in the allocation of land use types (possible patterns expressed in distance variation) is depicted as a probabilistic range by a Monte Carlo (MC) simulation framework based on stratified sampling. In a second step MC averages are aggregated again to the most probable landscape configuration, which is then used to derive the possible landscape configuration by spatial optimization. Simulation probability is evaluated on a pixel-basis and categorized in visual and numeric outputs per time step.

The presented study will show examples of two nested scenario runs for the policy scenarios business-as-usual (static restricted areas) and worst case (repeal of all restricted areas starting 2025) in the SSP2-4.5 setting and according results for the most probable landscape configuration and the possible landscape configuration based on a restoration paradigm.

This model is an advancement in Spatial Decision Support Systems as it allows to derive concrete action points that can be used by landscape planners and policy makers in cooperation with local stakeholders on a sub-national local to regional level.

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***Keywords**: SSP2-4.5, uncertainty, long-term land use change simulation, restoration, applied landscape planning and policy design*

Interpreting variable importance in multimethod research: Species distribution modelling for the Golden Bowerbird, in EcoCommons

S. Low-Choy[ab], D. Vasco[b], R. Clemens[c], and D. H. Kerlin[a]

[a] Centre for Planetary Health & Food Security, Nathan Campus, Griffith University (GU); [b] Griffith Institute of Educational Research, Mt Gravatt Campus, GU; [c] EcoCommons Australia, Nathan Campus, GU
Email: s.low-choy@griffith.edu.au

Abstract: A wide variety of quantitative methods have been devised for examining the relationship between an outcome (*Y* variable) and multiple predictors (*X* variables). Here we focus on species distribution models (SDMs) which seek the species-environment relationship, connecting species occurrence (presence/absence at various locations) to attributes of those locations, such as bioclimate or topography. As promoted by heavily cited and large-scale comparative studies, there is much to gain from comparing results from multiple SDM algorithms. However, such a multimethod approach makes strong demands from practitioners to not only understand, but also implement, multiple quantitative methods. Several computational platforms have been devised to streamline the technical aspects of multimethod SDM analyses, including the EcoCommons virtual laboratory and its predecessor, the BCCVL (Hallgren et al., 2016).

EcoCommons is designed to make it easy for end users to access several algorithms for single- and multi-species SDMs. Single-species SDMs in EcoCommons adopt algorithms from different quantitative paradigms: geography (such as minimum convex hull polygons), statistical modelling (such as logistic regression) and machine learning (such as Neural Networks, Boosted Regression Trees, and MaxEnt). Given this diversity of algorithms, the challenge is to create a "seamless" integrated platform that supports endusers in a largely consistent way across all algorithms, despite their differing quantitative paradigms. EcoCommons obliges by providing a consistent workflow for specifying inputs and outputs. Here we consider one output, *variable importance* (VI), which scores each predictor on its contribution to the SDM. This information may support ecologically meaningful explanations, to help, e.g.: develop understanding about species, assess management levers for enhancing conservation, or identify triggers for species responses to climate change.

To examine communication of VI across algorithms, in the multimethod context of a virtual laboratory, we use a SDM case study for the Golden Bowerbird (*Prionodura newtoniana*). This small yellow bird species is endemic to the Wet Tropics bioregion of Queensland, Australia. This case study helps clarify five key principles for interpreting VI in a multimethod context. Firstly, each SDM algorithm assesses a different facet of the species-environment relationship, so the nature of VI may vary across algorithms. Thus, it can be difficult to compare or summarise these different measures of VI across algorithms. Secondly, scoring VI in terms of predictive performance applies to all SDM algorithms (Thuiller et al. 2009). Thirdly, VI may be scored regarding its contribution to explanation and inference, however, this is specific to the choice of statistical model and computation, e.g. Akaike's Information Criterion for regression in a classical setting, or improvement indices for classification trees fit via recursive partitioning. Fourthly, VI is intertwined with data quality and relevance; e.g., proxies like elevation may improve predictions, yet confuse variable importance. Fifthly, VI is only meaningful for models that have adequate performance. In fact, the enduser ought to refine model settings, referring to predictive or explanatory performance, *before* assessing VI.

Overall, we conclude that, in order to interpret VI, end users must understand the nature of an SDM algorithm (and settings), specifically the role of variables in the model. This case study underlines the dangers of treating algorithms as "black-boxes", within broader concerns of explainability.

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Keywords: *Explainability, environmental niche modelling, virtual laboratory, quantitative paradigms*

An intercomparison of available geodatabases for characterising perennial systems

Danielle Verdon-Kidd[a], Angela Metcalfe[a], Steven G. Sandi[b]

[a] *School of Environmental and Life Sciences, The University of Newcastle, Callaghan, Australia*
[b] *School of Engineering, The University of Newcastle, Callaghan, Australia.*
Email: steven.sandirojas@newcastle.edu.au

Abstract: The Murray Darling Basin (MDB) in Australia contains a high proportion of freshwater systems that serve as hydrologic refugia for a wide range of species of fish, waterbirds, amphibians and many other fauna. These systems are of high importance for the conservation of Australian biodiversity, especially during dry periods when streamflow can cease. The natural cycle streamflows feeding these freshwater systems is highly variable and driven by diverse hydrological factors (Gallant et al., 2012). In the MDB, water availability is limited and environmental water is under increasing pressure from a range of threats, including changing climate, increasing water use for agriculture, human consumption, and industry development. Freshwater systems are expected to have significant impacts under the projections of climate change (Sandi et al., 2020), therefore, analysis of the current state of freshwater systems is of major importance for conservation of biodiversity and ecological assets, more so the analysis of perennial systems and their persistence throughout dry periods. Large scale geodatabases can provide very valuable information to inform the identification and analysis of perennial systems, but uncertainty or inconsistencies in large scale databases can be largely disinformative for analysis and modelling (Kauffeldt et al., 2013). Assessment of such databases is therefore required to test the quality of data before its implementation.

This study compares three continental extent and commonly used sources of surface water data to assess their accuracy for identifying perennial freshwater systems, specifically Geodata, Geofabric and WOfS. We show significant inconsistencies between the three geodatabases and highlight the challenges of defining water persistence using such databases. These inconsistencies can result in significant limitations for large scale studies and may limit our understanding of perennial systems. This research also implements hydrological modelling to extend historical flows within a selected catchment of the Murray Basin over the last century and it establishes the basis for the study of potential climate change impacts on water persistence and cease to flow events in the MDB. Implementation of available geodatabases to characterise the perenniality of waterbodies and streams can be aided by hydrological modelling, and providing accurate estimates of streamflows is therefore a key tool for future research, monitoring valuable sites, planning and optimising management plans.

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Keywords: *Geodata, Geofabric, WOfS, perennial systems*

Scaling the intensity of tropical cyclones for hazard assessment

Craig Arthur [a]

[a] *Place, Space and Communities Division, Geoscience Australia, Canberra, 2609, Australia*
Email: craig.arthur@ga.gov.au

Abstract: Understanding the potential changes in tropical cyclone (TC) intensity is a key component in estimating future changes in the likelihood of extreme wind speeds. For an internally consistent view on TC intensity (internally consistent with tracks and seasonal frequency), we have utilised tropical cyclone-like vortices (TCLVs) extracted from a set of eleven regional climate model (RCM) simulations performed by Queensland's Department of Environment and Science. TCLVs are a model representation of TC activity, and display qualitative characteristics of observed TCs, including negative vorticity maxima (in the southern hemisphere), co-located surface wind maxima and warm core temperature anomalies (Walsh, 1997). This provides seasonal frequency, track and intensity information driven by the RCM (which are in turn forced by global general circulation models), which can be used in stochastic TC hazard models.

The challenge with regional climate model data is the relatively coarse spatial resolution and the use of parameterised convective schemes to represent key physical processes that control the intensity of observed TCs (Walsh *et al.*, 2013). This results in detected TCLVs having much lower intensity than their real-world counterparts. Using the intensity data directly from TCLVs in stochastic hazard models will result in unrealistically low intensity distributions.

To overcome this challenge, we apply quantile delta mapping (QDM) to rescale the intensity of detected TCLVs. QDM (Cannon *et al.*, 2015) explicitly preserves relative changes in quantiles for simulated variables, and has been applied to precipitation extremes in climate modelling applications. QDM is applied to the lifetime maximum central pressure deficit of TCLVs, using observed values as the baseline distribution, as the central pressure deficit is the key intensity variable used in the stochastic TC model for estimating extreme wind speeds (Arthur, 2021). For a given reference period (1981-2010), systematic biases in the RCM distributions compared to the observational baseline are first corrected, producing consistent transformations of the RCM intensity distributions.

When applied to projected time periods, the algorithm produces a range of projected changes in intensity distributions, which preserve the underlying climate sensitivity of the quantiles for each RCM. This highlights the sensitivity of projected TC activity to the formulation of the driving RCMs. The resulting scaled intensity is validated against theoretical measures of potential intensity (Bister and Emanuel, 1998; Holland, 1997) derived from the RCM outputs. In some cases, the scaled RCM TCLVs have intensities much higher than observed records, and exceeding the theoretical potential intensity. Reasons for this outcome are noted, but a full analysis is beyond the scope of this short presentation.

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Keywords: *Tropical cyclones, climate, extremes, hazard*

Improving climate resilience of agricultural systems through the development of drought vulnerability curves

I. Borzì [1], **B. Monteleone** [2], **B. Bonaccorso** [1] **and M. Martina** [2]

[1] *Department of Engineering, University of Messina, Italy*
[2] *IUSS – Institute for Advanced Study of Pavia, Pavia, Italy*
Email: iolanda.borzi@unime.it

Abstract: The Po River Basin is Italy's main agricultural land and accounts for 35% of the country's production. In Italy, 50% of the country's water withdrawal is allocated to agriculture according to ISTAT, but in the Po basin irrigation is widely applied with 53%, 42% and 37% of irrigate arable land in Lombardy, Veneto and Piedmont (the three wider regions of Po area) respectively. The basin was struck by multiple droughts over the past years. Previous studies highlighted that the 2003-2008 events caused huge economic impacts on the agricultural sector, with the 2005-2007 period accounting for around 1.857B€ of losses. The development of quantitative models to establish a relationship between water deficit and crop yield losses can help in reducing losses by improving the water allocation mechanisms to provide water when it is actually needed. This study develops crop specific vulnerability curves tailored to the Po River basin context. The curves show the relationships between water deficit and yield losses during various crop growth stages (vegetative, flowering and yield formation).

The Agricultural Production System sIMulator (APSIM) was used to reproduce the plant growth. The crop model has been implemented specifically to provide accurate predictions of crop production in relation to climate. The model was initialized with daily meteorological parameters (rainfall, average, maximum and minimum temperature, solar radiation) from the E-OBS dataset, a gridded weather dataset with a 10km spatial resolution available for Europe only. The dataset is based on the interpolation of observational data. The spatial coverage is good over the Po basin area. Soil texture was retrieved from the ISRIC dataset, while the agricultural practices (such as sowing date, fertilizer amount, etc) were derived from Lombardy region guidelines for the year 2020.

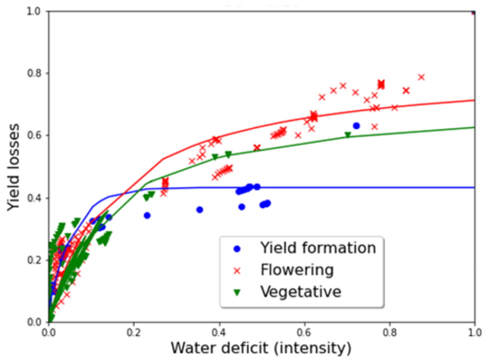

Figure 1. Example of vulnerability curves for maize

At first reference yield for a specific season (the yield in the absence of any water stress during the entire growing season) was computed. Then, the reduced yield for the same season was derived introducing a water stress in a single growth stage by progressively reducing the precipitation amount during the growth stage. The yield reduction was expressed as one minus the ratio between the reduced yield and the reference yield. From the APSIM model crop water deficit for each season and each growth stage was derived. The relationship between yield reduction and water deficit was plotted to derive the vulnerability curves. Data points were fitted to asymmetric logistic functions.

Two crops were considered: maize and winter wheat. The developed vulnerability curves for the selected crops are in agreement with the vulnerability functions proposed by the FAO, which has underlined the importance of avoiding water stress during flowering to get high yield. Vulnerability curves here developed represent a useful tool to support future decision-making strategies under climate risk conditions. Vulnerability curves can help improving resilience in agriculture, as they represent easy to use tools to warn farmers about climate vulnerability of their crops, and consequentially to support more resilient crop development and planning.

Keywords: *Vulnerability curves, droughts, agriculture, climate resilience*

Modelling future changes in social vulnerability and bushfire risk

E. Moore [a], Y. Zhar [a], P. Radford [a], M. O'Callaghan [a], H.R. Maier [a], G. Riddell [a], H. van Delden [a, b], M. Wouters [c]

[a] School of Civil, Environmental & Mining Engineering, University of Adelaide, Adelaide, South Australia, [b] Research Institute for Knowledge Systems, Maastricht, Netherlands, [c] South Australian Department for Environment and Water, Adelaide, South Australia
Email: holger.maier@adelaide.edu.au

Abstract: A natural hazard becomes a natural disaster when individuals, communities and infrastructure are impacted. The impact of a natural disaster is a function of the type and magnitude of the hazard, and the vulnerability of the people and assets exposed to the hazard. Consequently, bushfire risk is not only a function of bushfire likelihood and intensity, but also the social vulnerability of affected communities.

In this paper, a framework is presented that enables the spatial distribution of bushfire risk to be quantified by considering bushfire likelihood and social vulnerability. The framework also caters to the assessment of how this risk could change into the future in response to climate change and socio-economic development.

The framework is applied to the case study of Greater Adelaide, South Australia. The current distribution of social vulnerability is calculated based on a number of indicators and the current distribution of bushfire likelihood determined using the Unified Natural Hazard Risk Mitigation Exploratory Decision Support System (UNHaRMED), enabling the spatial distribution of current bushfire risk to be determined based on social vulnerability.

Plausible spatial distributions of future bushfire risk based on social vulnerability are obtained in response to a number of climate and socio-economic exploratory scenarios. The impact of climate change scenarios on bushfire likelihood is quantified with UNHaRMED. The impact of the socio-economic scenarios on social vulnerability is quantified using a combination of changes in the distribution of land use and population with the aid of UNHaRMED, as well as "clues" in the narrative scenario storylines about likely changes in factors affecting social vulnerability.

The results indicate that future changes in social vulnerability are likely to affect long-term bushfire risk in greater Adelaide, with spatial distributions of social vulnerability and bushfire risk changing in different ways under different plausible future scenarios. This enables areas of emerging risk to be identified, opening the door to long-term risk-reduction strategies to be targeted to these high-risk regions.

Keywords: *Social vulnerability, bushfire risk, future risk, scenarios*

Developing an Adaptive Evacuation Simulation Framework based on Agent Performance Dynamics

T. A. Rollan[a,b], **L. Marquez**[a] **and C. Chua**[b]

[a] CSIRO Data61, Clayton, Australia, [b] Swinburne University of Technology, Hawthorn, Australia
Email: trollan@swin.edu.au

Abstract: The benefits of evacuation drills for disaster preparedness are not yet well-established. Virtual reality and serious games (SG) application to evacuation simulation were proven to be effective in overcoming limitations of traditional emergency training approaches with a significant increase in the trainees' knowledge and self-efficacy. Further, human behavioural modelling is a critical component of evacuation simulation.

This study will develop an evacuation simulation framework, incorporating various approaches such as cluster analysis, structural equation modelling, agent-based modelling, cognitive modelling and serious games. Although the case study focuses on earthquake, the components of the evacuation framework is designed to be applicable to other types of disaster requiring evacuation. The study's contributions include 1) a cognitive agent model, incorporating experiences, personality, emotions and behavioural decision-making, 2) an implementation of the behavioural modification approach as the foundation for efficient evacuation, 3) a reproduction of a multi-storey structure to add layers of complexity to the evacuation, and 4) a decision support tool to evaluate existing strategies and propose new strategies that will adapt to agent performance dynamics.

The study site is a university with a student population of approximately 8000, located at around 8.4 km from a major earthquake fault line and lacks open spaces for evacuees and emergency responders. Therefore, the site is significantly at high risk for a large number of casualties once the anticipated earthquake of extreme magnitude with a minimum of 7.2 strikes. Four scenarios are being considered including Scenario 1 which represents a regular enrolment day when student numbers are expected to be moderately higher than a regular school day. Scenario 2 represents the peak time slot on a regular school day when the population is at its maximum. Scenarios 3 and 4 are both days with extra-curricular events when the number of visitors is at its maximum.

An online earthquake evacuation survey was designed to conduct population profiling for the occupants of the university. Cluster analysis will divide the survey participant population into evacuee groups in terms of their demographic information, personality traits and their responses to questions on past and future behaviour and decision-making during evacuations. Preliminary implementation in Unity game development software involved simulation runs using an initial version of the agents being aware of the exit locations. For each timestamp, the simulation engine stores information per agent including a generated unique agent number ID, role including faculty and student, current location such as first floor and parking lot, 3D coordinates and the evacuation state. The evacuation simulation component will produce evacuee count vs time and evacuee floor level vs time graphs, and evacuee route and heat maps. The decision support component will produce a set of proposed evacuee schedule and route assignments. The proposal for the evacuee population profile composition will be based on the experiments that will be conducted focusing on how behavioural modification can improve evacuation performance.

The succeeding version of the implementation will apply the results of the survey on the agent model and perform the simulations on the four identified crucial scenarios.

Keywords: *Evacuation simulation, agent-based modelling, behavioural modelling, emergency decision support, disaster management*

INDRA – Climate Resilience Platform for the City of Makassar

V. C. N. Weeraratne [a], **M. Prakash** [a], **R. C. Z. Cohen** [a] **and N. Garg** [a]

[a] *CSIRO Data61, Clayton, Victoria, Australia*
Email: Vihan.Weeraratne@csiro.au

Abstract: INDRA (https://research.csiro.au/indra) is a web-based climate and hazard risk analytics and visualisation platform developed by CSIRO Data61 to solve the challenges associated with present day climate and future climate change related datasets. These challenges include accessibility of datasets and the interoperability with other datasets such as demographics and infrastructure. INDRA Makassar was developed to solve these challenges for the City of Makassar in the province of South Sulawesi in Indonesia, thereby developing a climate resilience framework for the rapidly growing region. The INDRA platform is currently being expanded to reach out to a broad range of stakeholders in Australia first and globally thereafter. The INDRA platform for Makassar was supported by the Asian Development Bank as a part of the ASEAN Australia Smart Cities Trust Fund (AASCTF). It was developed with inputs from Ramboll and the University of Hasanuddin in Makassar. A comprehensive collection of climate, demographic, infrastructure, and region/place datasets were presented on INDRA Makassar as easily mappable and downloadable layers. Several climate and hazard datasets across different spatio-temporal scales were deployed to help decision-makers easily understand risks and social vulnerability involved with climate change. These layers included sea-level rise inundation layers, projected climate layers such as temperature and precipitation, historical climate layers, current and projected population layers and land-use layers. Infrastructure layers included roads, drainage networks and hospitals.

The already modelled climate projections and historical climate data for maximum temperature, precipitation and minimum temperature were derived from the WorldClim v2.1 dataset (Eyring et al., 2016; Fick and Hijmans, 2017). The sea level rise inundation layers were bathtub fill (modelling) layers resulting from imposing sea-level rise values to current high tide levels for South Sulawesi and provided a good understanding of high-risk areas for different sea-level rise scenarios expected in the future. The modelling of inundation layers involved a detailed literature study and utilised the best available terrain and bathymetric data for the region. Furthermore, multiple datasets can be combined and viewed to better understand challenges that the region may face in the future. For example, the predicted population layer can be combined with any of the climate layers to better understand communities at risk. The INDRA framework will help urban planners to make the City of Makassar future-proof by making the city more resilient to climate change by providing easily accessible climate information on multiple time scales including historical data and future climate projections.

Keywords: *Climate change, climate data, climate resilience, urban risk analysis, sea-level rise*

Coastal inundation modelling and adaptation assessment for the Bellarine Peninsula

V. C. N. Weeraratne [a], R. C. Z. Cohen [a], R. Roob [b] and M. Prakash [a]

[a] *CSIRO Data61, Clayton, Victoria, Australia,* [b] *City of Greater Geelong, Victoria, Australia*
Email: Raymond.Cohen@csiro.au

Abstract: The Bellarine Peninsula is located south west of Melbourne, Victoria and parts of the coastal jurisdiction are managed by the City of Greater Geelong (CoGG). It has coastlines on Bass Strait, Port Phillip Bay and Corio Bay, with some hotspots that are vulnerable to coastal inundation under present day tidal extremes. This inundation risk will increase with any future sea level rise (SLR). CoGG is interested in understanding adaptation infrastructure options that could be implemented to protect nine highly vulnerable coastal hotspots around the Bellarine Peninsula. In this study the inundation across six different simulation regions were modelled using CSIRO Data61's hydrodynamic and hydraulic modelling toolkit, CFAST. Scenarios involving 1% AEP peak tides under six different SLR conditions (0.0 m up to 1.4 m superimposed on to the baseline 1% AEP tide levels) were considered. Crest levels for the coastal adaptation structures were recommended based on the modelled peak still water level (SWL) for each of the hotspots derived from CSIRO's extreme sea level tool, Canute. Additionally, the effectiveness of local adaptation measures were modelled for the same scenario list. Other inputs integrated into the CFAST modelling framework included terrain and bathymetry data, pipe drainage networks, rainfall, catchment flows, Manning's drag coefficient and soil infiltration parameters.

The challenges of climate data accessibility and interoperability with infrastructure datasets were addressed by delivering the modelling results on CSIRO Data61's climate and hazard risk analytics and visualisation platform, INDRA (https://research.csiro.au/indra). INDRA incorporates a range of datasets which can be viewed in conjunction with the modelling results whilst including analytics capabilities. The allows better understanding of the differences in inundation risks for different SLR scenarios and adaptation infrastructure. The analytics included flood extent progression by the amount of SLR, flood extents comparing the effectiveness of the proposed adaptation measures and a quantitative infrastructure impact assessment on building parcels in the region. The simulation results showed that the modelled adaptations were all beneficial (at reducing flood impacted infrastructure in the simulated regions) for the critical SLR value of 0.8 m. For a SLR of 1.1 m the adaptations became ineffective for Portarlington and Barwon Heads/Ocean Grove. Whereas for the SLR of 1.1 m the adaptations were still effective for Moolap, St Leonards and Queenscliff. All adaptations were ineffective for the extreme SLR of 1.4 m. For the 0.8 m SLR cases the most adaptation benefit occurred for simulation regions of Queenscliff (422 less buildings impacted), Barwon Heads/Ocean Grove (64 less buildings impacted), and St Leonards (60 less buildings impacted). This methodology enables the stakeholders to make improved data driven decision making about adaptation infrastructure design and investment.

Keywords: *Flood modelling, coastal inundation, adaptation, sea level rise, infrastructure impacts*

CORDEX Update

J.P. Evans [a] and **M.J. Thatcher** [b]

[a] *Climate Change Research Centre and ARC Centre of Excellence for Climate Extremes, University of New South Wales, Sydney, New South Wales, Australia*
Email: Jason.evans@unsw.edu.au
[b] *Climate Science Center, CSIRO Oceans and Atmosphere, Melbourne, Victoria, Australia*
Email: marcus.thatcher@csiro.au

Abstract: The COordinated Regional climate Downscaling EXperiment (CORDEX) is an initiative backed by the World Climate Research Programme (WCRP). The goal of the initiative is to provide regionally downscaled climate projections for most land regions of the globe, as a compliment to the global climate model projections performed within the Coupled Model Intercomparison Project (CMIP) program. The CORDEX dataset provides a link to the impacts and adaptation community through its better resolution and regional focus. CORDEX-CMIP5 projections are available through available through the Earth System Grid Federation. CORDEX-Australasia currently has 20 ensemble members including the 6 CORDEX-CORE simulations. Participation in CORDEX is open and any researchers performing climate downscaling are encouraged to engage with the initiative.

The CORDEX-CMIP6 model evaluation framework consists of RCM simulations performed using the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 re-analysis as "perfect boundary conditions". The climate projection framework is based on CMIP6. CORDEX prioritizes the GCM experiments using emission scenarios known as SSP3-7.0 and SSP1-2.6 which represent a low and a high-level emission scenarios. Secondary simulations using the SSP5-8.5 ans SSP2-4.5 A number of groups have started performing simulations for the CORDEX-AustralAsia domain. This ensemble will continue to grow over the next couple of years.

As well as the future projections CORDEX is focused around five key regional challenges: Added value, Human elements, Coordination of Regional Coupled Modelling, Precipitation and Local Wind systems. In addition to the key challenges, four cross cutting themes have been identified: Water resources and Hydrological cycle, Development of process based metrics, the water-energy nexus and Extremes. Flagship Pilot Studies are one mechanism through which CORDEX will attempt to address these issues.

As well as releasing the CORDEX-CMIP6 experiment protocol, CORDEX has also recently released a white paper on future scientific challenges for CORDEX. In this talk I will provide an update on the current status of these CORDEX initiatives.

Keywords: *Regional climate model, CORDEX, Australasia*

RCM performance sensitive to land surface models

Fei Ji [a], Giovanni Di Virgilio [a], Jason P Evans [b], Nidhi Nishant [a], Chris Thomas [b], Eugene Tam [a] and Kathleen Beyer [a]

[a] *Climate Research, Climate & Atmospheric Science Branch, science Economics & Insights Division, NSW Department of Planning, Industry and Environment, Sydney, 2150, Australia*
[b] *Climate Change Research Centre, University of New South Wale, Sydney, 2052, Australia*
Email: fei.ji@environment.nsw.gov.au

Abstract: Land Surface Models (LSMs) are important components of regional climate models (RCMs), which help to capture the water, energy, and momentum exchange between the land surface and the atmosphere, providing lower boundary conditions to the atmospheric models.

In NARCliM1.0 & 1.5, the Unified Noah LSM was used, which may contribute to large wet and cold biases in reanalysis and GCM driven regional climate simulations. Here, we test the varying performances of a suite of 78 different physical parameterisations of the weather research and forecasting (WRF) RCM including three land surface models (CLM, Unified Noah and Noah-MP with default setting) for the selection of the best performing RCMs for the NSW Government's NARCliM2.0 regional climate modelling project. Each land surface model is combined with other physics schemes including three Planetary Boundary Layer schemes (PBL), two Microphysics schemes (MP), two Cumulus schemes (CU). Simulations are forced by ERA-Interim and run for Nov-Dec 2015 and through 2016 at 4 km for southeast Australia and 20km for Australasia.

The evaluation results indicated that the ensemble of simulations using Noah-MP is generally much better than those using Unified Noah and CLM. Noah-MP constantly performs better than Unified Noah and CLM when it is combined with different PLB, MP and CU physics schemes. Further tests to replace the default setting with three specific settings in Noah-MP show that Noah-MP with those specific settings performs even better than Noah-MP with the default setting. Physical mechanisms underlying the results are under investigation.

Keywords: *NARCliM, Land Surface Model (LSM), CLM, Unified Noah, Noah-MP, Weather research and forecasting model (WRF)*

How well do regional climate models maintain variable dependency

Y. Kim [a], **J.P. Evans** [b], **and A. Sharma** [a]

[a] *School of Civil and Environmental Engineering, University of New South Wales, Sydney, New South Wales, Australia,* [b] *Climate Change Research Centre and ARC Centre of Excellence for Climate Extremes, University of New South Wales, Sydney, New South Wales, Australia*
Email: youngil.kim@student.unsw.edu.au

Abstract: The applicability of global climate models (GCMs) is limited by the fact that their spatial and temporal resolutions are insufficient to use at fine scales. Regional climate models (RCMs), where GCM data are used to provide input boundary conditions, are commonly used to resolve finer resolution. Unfortunately, their application is hindered by systematic biases in boundary conditions that can be propagated into RCM outputs. In order to deal with these biases, various bias correction methods ranging from simple scaling to sophisticated techniques have been applied to the input boundary conditions.

These bias correction methods, however, have focused on correcting individual variables without consideration for physical relationships among the atmospheric variables that define the RCM input boundary conditions. This may lead to physical inconsistencies, impacting the model outputs in dynamically linked fields.

This study focuses on where or not the RCM simulations can preserve dependence within and across atmospheric variables as a consequence of bias corrections in the input boundary conditions. Two univariate bias correction methods, mean and nested bias correction which includes corrections for lag-1 autocorrelations, are applied over 31-years with the first year negated to remove spin-up effects. To assess dependencies of variables over time or space, this study uses correlation length (CL), which focuses on temporal and spatial dependence. Multivariate dependence is ascertained using a pairwise cross-correlation coefficient at every grid cell.

The GCM used here is the Commonwealth Scientific and Industrial Research Organization's Mk3.5 (CSIRO), and the Weather Research and Forecasting model (WRF) with dynamical core (ARW) is the RCM used in this study. The reanalysis model is the European Center for Medium-Range Weather Forecast's (ECMWF) ERA-Interim (ERA-I). The ERA-I driven RCM simulation is used as an "observation" in this study. The downscaling is performed over the Australasian Coordinated Regional Climate Downscaling Experiment (CORDEX) domain.

It is clear from the results that the RCM simulations with univariate bias-corrected GCM boundary conditions produce improvement for temporal and spatial dependence. The results also show that the RCM simulation produces a similar spatial pattern feature of the surface variables used in this study regardless of the bias correction of the RCM input boundary conditions. This study highlights no substantial improvement in both RCM simulations with uncorrected and univariate bias-corrected GCM boundary conditions for multivariate dependence, suggesting the need for alternatives to correct the physical relationships between the variables in the boundary conditions.

Keywords: *Regional climate model, boundary conditions, bias correction, variable dependency*

The impact of bias correction on the climate change signal

Justin R. Peter [a], **Pandora Hope**[a], **Elisabeth Vogel**[a] **and Greg Kociuba**[a]

[a] *Bureau of Meteorology, Melbourne, Australia*
Email: justin.peter@bom.gov.au

Abstract: Bias correction is the process of adjusting model output to observations, often by matching the quantiles of the modelled field to those of observations. It is often applied to the output of Global or Regional Climate Models (GCMs/RCMs) to serve as input for impact models, which in turn are used to provide products and services to inform adaptation decisions. However, the use of bias correction to correct variability has received criticism since it can cause implausible climate change signals or alter variable interrelationships (Maraun et al. 2017).

The Australian Bureau of Meteorology has recently undertaken the National Hydrological Projections project (NHP) to produce an ensemble of projections of runoff, soil moisture and potential evapotranspiration as part of their Australian Water Outlook service. The NHP output was produced by applying three statistical bias correction methods to the output of four GCMs and one method to the CCAM RCM, resulting in a 16-member ensemble. The bias corrected variables were precipitation, maximum and minimum temperature, near-surface wind speed and downwelling solar radiation. The statistical bias correction algorithms applied were the ISIMIP2b (Hempel et al. 2013), MRNBC (Mehrotra et al. 2018) and QME (Dowdy 2020) methods. They are all variants of quantile-quantile matching with differences regarding their treatment of the climate change signal trend (ISIMIP2b), inter-variable correlations (MRNBC) or treatment of extreme events (QME).

Here, we examine the impact these bias correction methods have on the original GCM climate change signal, including their impact on wet/dry spell length, indices of extreme temperature and precipitation, and their effect on the climate change signal over complex topography. Individually, the bias correction methods cause conflicting modifications to the original GCM or RCM signal, which results in an increase in the ensemble spread of the bias-corrected ensemble when compared to the original 4-member GCM ensemble. We discuss the implications for communication of uncertainties in the NHP projections.

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Keywords: *Bias correction, climate projections, downscaling, hydrology*

High-resolution dynamical downscaling over Southeast Asia: Perfect vs Imperfect Boundary Conditions

V. Prasanna, Sandeep Sahany, Aurel Moise, Xin Rong Chua, Chen Chen, Gerald Lim and Muhammad Eeqmal Hassim

Centre for Climate Research Singapore, Singapore 537054
Singapore
Email:Venkatraman_PRASANNA@nea.gov.sg

Abstract: In dynamical downscaling, biases in lateral boundary conditions obtained from coarser models can play an important role in the dynamically downscaled simulations. As a part of Singapore's Third National Climate Change Study, dynamical downscaling has been carried out over Southeast Asia (SEA; 79E-160E;16S-24N), using the Singapore Variable Resolution Regional Climate Model (SINGV-RCM; an adapted version of Singapore's operational NWP model (Timbal et al., 2019)) using perfect boundary conditions (ERA-5) and a CMIP6 GCM (MIROC-6) at 8km horizontal resolution. The SINGV-RCM is forced with ERA-5 reanalyses data for a 36-year period (1979-2014) at 8km resolution over SEA with regular update of the sea surface temperature at 6-hr interval; further, a similar simulation is carried out using MIROC-6 GCM forcing data for a 60-year period (1955-2014). The last 20-year period (1995-2014) from the 2 simulations with reliable high-resolution observation (merged in-situ and satellite) is selected for evaluation. Rainfall characteristics including the diurnal cycle and extremes from the two simulations evaluated against observations will be presented.

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Keywords: *Singapore's Third National Climate Change Study, high-resolution dynamical downscaling, SINGV-RCM, CMIP6 GCM (MIROC-6), Perfect vs Imperfect Boundary Condition*

Added value of regional climate projections for Australia

Christian Stassen[a], Marcus Thatcher[b], Chun-Hsu Su[a], Jason Evans[c], Benjamin Ng[b], Andrew Dowdy[a], Harvey Ye[a], Ian Watterson[b], Giovanni Di Virgilio[d] and Peter Steinle[a]

[a] Bureau of Meteorology, Melbourne, Australia
[b] CSIRO, Melbourne, Australia
[c] University of New South Wales, Sydney, Australia
[d] NSW Department of Planning, Industry and Environment
Email: Christian Stassen (christian.stassen@bom.gov.au)

Abstract: Climate projections are a valuable tool for understanding the likelihood of future climate changes and impacts in the Australian region, including for enhanced planning and preparedness in relation to phenomena such as wildfires, cyclones and rainfall extremes. With many types of extreme events projected to become more pronounced with climate change including in Australia (CSIRO and Bureau of Meteorology 2015), there is an increasing need for robust fine-scale projections of key climate variables. Spatially and temporally high-resolution climate model output is generally needed in climate change impact and adaptation studies particularly when conducted on regional and local scales. Regional climate models (RCMs) provide such information by dynamically downscaling global climate model (GCM) information to these finer scales. This allows them to account for local details such as complex topography, land-sea contrasts and regional surface characteristics that cannot be resolved or considered in GCMs. Consequently, RCMs have the potential to more accurately simulate processes relating to precipitation and extreme events in areas with complex landscapes.

For the Australian domain three main modelling systems exist. That is NARCliM (New South Wales and Australian Capital Territory Regional Climate Modelling) which uses the Weather Research and Forecasting (WRF) model, the Conformal Cubic Atmospheric Model (CCAM) and the Bureau of Meteorology Atmospheric Regional Projections for Australia (BARPA) framework using the Australian Community Climate and Earth-System Simulator (ACCESS) model.

For RCMs to be useful it is essential that they improve some aspect of the simulated climate compared to a global model i.e., the RCM adds value compared to the GCM. The added value (AV) of the three RCMs is evaluated over the historical period by comparing the model outputs against observations (Di Luca et al. 2016) and the potential for added value (PAV) is assessed for the future projections by measuring how much the RCM climate change signal differs from its host GCM (Di Virgilio et al. 2020). Ultimately, both measures, AV and PAV, are combined to a single normalised measure: the realised added value (RAV) for all RCMs.

This work highlights regions, seasons, and climate variables for which the three RCMs demonstrate realised added value over their GCM counterparts and demonstrates the benefits of using a multi-model approach.

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Keywords: *Regional climate models, climate projections, atmospheric modelling*

BARPA: Towards seamless high-resolution atmospheric modelling from past to future outlooks

Chun-Hsu Su[a], Christian Stassen[a], Harvey Ye[a], Andrew Dowdy[a], Samuel Bell [a], Acacia Pepler[a], Chiara Holgate[a], Andrew Brown[a], Simon Tucker[b] and Peter Steinle[a]

[a] *Bureau of Meteorology, Australia*
[b] *Met Office Hadley Centre, Fitzroy Road, Exeter, EX1 3PB, United Kingdom*
Email: Chun-Hsu Su (chunhsu.su@bom.gov.au)

Abstract: Australia's climate is highly variable and extreme weather events range from extreme precipitation to drought, heatwaves, cyclones, thunderstorms and bushfires. With many types of extreme events projected to become more exacerbated with climate change including in Australia (CSIRO and Bureau of Meteorology, 2015), there is an increasing need for robust fine-scale projections of key climate variables. Spatial and temporal high-resolution climate model output is generally needed in climate change impact and adaptation studies particularly when conducted on regional and local scales.

The Bureau of Meteorology Atmospheric Regional Projections for Australia (BARPA) is a new regional climate modelling framework set up for the Australian region. BARPA dynamically downscales global climate information to fine temporal and spatial resolutions using the atmosphere and land model components from the Australian Community Climate and Earth-System Simulator (ACCESS): the UK Met Office Unified Model (UM) and the Joint UK Land Environment Simulator (JULES). Here we report the moderate resolution framework of BARPA – BARPA-R (Su et al., 2021) – with a horizontal resolution in the order of 10 km which covers the Australasian CORDEX domain. New physics parameterisation schemes of BARPA-R are examined and challenges of this large model domain, such as model drift, are discussed. The output is assessed against observation-based data. This work demonstrates that BARPA yields stable and realistic simulations of near-surface meteorological parameters and provides added regional information to the host global data.

Using the ACCESS model provides the benefit of similarities to other weather and climate products provided by the Bureau of Meteorology including historical reanalysis, operational weather forecasting, and seasonal prediction. The consistency of climate products is part of broader goals towards providing seamless and consistent services across a range of time scales. It is intended that BARPA-R will help contribute to a broader set of regional climate models (CCAM and WRF) in the NextGen Climate Projections (NESP Earth Systems and Climate Change Hub, 2021) for understanding future changes in climate extremes, particularly near features of topography, urban areas, and coasts.

The initial set of BARPA projections have been developed and tested for the Electricity Sector Climate Information (ESCI) project and will be extended to support the Australian Climate Service (ACS).

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Keywords: *Regional climate models, Climate projections, ACCESS, CORDEX, Atmospheric modelling*

Spotfire Utilisation Project: Development of a mapping tool for regions prone to vorticity-driven lateral spread

R.L. Badlan [a] and **J.J. Sharples** [a b c]

[a]*School of Science, University of New South Wales, Canberra, ACT 2600, Australia.*
[b]*Bushfire and Natural Hazards Cooperative Research Centre, East Melbourne, Vic. 3002, Australia.*
[c]*ARC Centre of Excellence for Climate Extremes, UNSW Canberra, ACT 2600, Australia*
Email: r.badlan@adfa.edu.au

Abstract: Extreme wildfire development begins when a small fire transitions to a larger fire whch may then escalate to a mass or areal fire. One such trigger for this dynamic fire spread is a phenomenon known as vorticity-driven lateral spread (VLS), whereby the fire spreads laterally along ridgelines. Prediction of such events can be improved using a wind-terrain filter. This filter is a tool to aid in the identification of regions of the landscape that are prone to mass spotting and other dynamic fire behaviours associated with VLS. It is designed to be used by Fire Behaviour Analysts (FBANs) who may then use the information to influence decision-making when deploying resources and personnel.

Findings from previous research, which identified conditions that are conducive to VLS, were then used to create a mapping overlay identifying where slopes are sufficiently steep and the ridgelines orientated in a particular direction. However, as the distributions of slope vary with the resolution of the digital elevation model (DEM), the relationship between resolution and slope threshold was first determined.

The filter uses both the first- and second-order directional derivatives (slope and curvature respectively). The first-order and second-order wind-terrain filter enables the user to identify parts of the terrain which are sus-ceptible to VLS through its established association with steep or broken leeward-facing terrain elements. This is achieved using terrain attributes such as topographic slope, aspect, and profile curvature, as well as environ-mental variables such as the wind speed and direction.

This mapping tool is then applied to a case study from 2020 that took place in Montana, USA. Using the forecast data, the VLS filter was applied to the initial fire perimeter to to determine whether it highlighted areas where lateral spread occurred. The filter correctly identified VLS areas and, when interpreted with the forecast wind and those regions at risk, clearly indicated the approximate direction and the final burn area of the fire.

Keywords: *Spotfires, dynamic fire behaviour, GIS, digital elevation models, extreme fires*

Bushfire propagation speed: Combining the effects of wind and slope

S. Berres [a] and **N. Cárcamo** [b]

[a] *Universidad del Bío-Bío, Chillán, Chile*
[b] *Universidad Católica del Maule, Talca, Chile*
Email: Stefan.Berres@gmail.com

Abstract: In this contribution the effect of slope inclination on the bushfire propagation speed is studied. The slope effect is estimated in an inverse problem setup. As observation data, real fire scenarios are given in terms of maximum fire expansions. With the knowledge of the initial ignition location, the front perimeters can be determined in any direction. The direct problem is formulated as a mathematical model of surface bushfire. It is expressed in a functional form, where the front propagation speed depends on wind and slope. The fuel material as predominant factor is given as a constant, i.e. no heterogeneous combustible effects are considered, and the effects of humidity are neglected. The observation data are given as radial front propagation perimeter. As model and data are two dimensional, the wind impact is decomposed in speed and direction; the speed is the maximal speed in wind direction, such that in the orthogonal direction to the wind there is zero speed and negative maximum speed in the opposed wind direction. In the model, the speed parameters are fixed for the overall domain, whereas the inclination is known from topographical data.

The parameter identification problem is formulated as a nonlinear optimization problem, where the distance of the parametric model to the data is minimized by the optimal parameter set. The observation data give the distance reached by the propagation front. Though the radial perimeter data are two dimensional, covering all 360 degree directions, the model decouples the directions, establishing for each direction a one dimensional model. In this model simplification it is assumed that the fire spreads in each direction separately, without cross-directional interference. The mathematical model describes the propagated pathway simultaneously for each direction by a differential equation, where the change of position in time is given by the velocity model, that expresses the velocity in terms of wind and slope. In general, the model solution at given time points can be compared with the measured advance of the propagation front of a particular fire. The measurement data of final bushfire perimeters is provided by the National Forest Corporation of Chile (CONAF). The used experimental data is implemented manually from a shapefile type file using Google Earth tools. The methodology of solving the inverse optimization problem is implemented computationally on the Matlab/Octave, with plans to migrate to Python.

The sensitivity analysis gives only a weak validation of the slope dependence. As a conclusion, more data than the final perimeter data are required. In standard situations, satellite images have been available only once a day, and firefighters are not yet by default equipped with GPS sensors that might enable local fire-front tracking. The expectation is that in the context of the *big data* paradigm, i.e. within the omnipresence of ubiq-uitious computing, a denser data coverage is going to be available, that might be coordinated by corresponding projects. Regarding the model, certainly the simplification of a two-dimensional scenario by simultaneous one-dimensional models is restrictive, especially in the perspective that the interaction with meteorological aspects requires a three-dimensional model, that even might be enhanced by multiple scales. Yet, the dif-ferent model types might contribute to the discussion in the context of the availability of data and different comprehension levels of involved users or stakeholders. Thus, the presented model is going to be still valid for didactic purposes and as an intermediate parameter identification approach, that goes fine within an open modelling methodology.

Keywords: *Bushfire, propagation perimeter, parameter estimation, sensitivity analysis*

Extreme bushfire projections for Australia using a standardised method

Andrew J. Dowdy[a], **Marcus Thatcher**[b], **Tony Rafter**[b], **Jason Evans**[c], **Hua Ye**[a], **Chun-Hsu Su**[a], **Christian Stassen**[a], **Acacia Pepler**[a], **Samuel Bell**[a] **and Peter Steinle**[a]

[a] *Bureau of Meteorology, Docklands, Australia*
[b] *CSIRO Oceans and Atmosphere, Aspendale, Australia*
[c] *University of New South Wales, Sydney, Australia*
Email: andrew.dowdy@bom.gov.au

Abstract: The influence of anthropogenic climate change on extreme bushfire weather in Australia is assessed using a standardised method for projections information. The method steps comprise a review and synthesis of a comprehensive range of factors based on observations, modelling and physical process understanding. The resultant lines of evidence are then used to guide the production of projections data and confidence assessments. Projections are produced based on global climate model output as well as dynamical downscaling data using three regional climate modelling approaches (CCAM, BARPA and NARCliM/WRF). The projections data are calibrated using quantile matching methods trained on observations-based data, with a particular focus on the accurate representation of extremes. The resultant projections data include nationally consistent maps of bushfire weather indices corresponding to the 10-year average recurrence interval (i.e., return period) around the middle of this century (2040-2059), with a focus of the discussion on regions around southern and eastern Australia during summer as needed for some risk assessment applications. The projections data are also available for other seasons and time periods throughout this century, as well as for other metrics of extreme or average conditions. The results for southern and eastern Australia during summer show more dangerous bushfire conditions (high confidence in southern Australia; medium confidence in eastern Australia) attributable to increasing greenhouse gas emissions.

Keywords: *Bushfires, projections, regional downscaling, hazards, wildfire*

A water suppression model for wildfires

J.E. Hilton [a], **A. Sullivan** [b], **M. Plucinski** [b] **and W. Swedosh** [c]

[a] *Data61, CSIRO, Clayton South, VIC 3169, Australia*
[b] *Land & Water, CSIRO, Black Mountain, ACT 2601, Australia*
[c] *Land & Water, CSIRO, Clayton South, VIC 3169, Australia*
Email: james.hilton@csiro.au

Abstract: The ability to model water suppression efforts on wildfires is useful for both operational firefighting as well as testing control and containment strategies. Models developed to date have used heat energy balance relations to estimate the flow of water needed to extinguish a wildfire, but these have some limitations. These include expressing extinguishment criteria in the form of a steady state water flow relation and the inability to model the heat retention within the fuel bed. The modelling of heat retention is necessary as although water can cool the bed below the point of ignition, once the water has evaporated the bed can potentially re-ignite due to residual heating from the lower layers. Here we detail a water suppression model based on temperature and heat flow within the bed. The model is dynamic, can be applied spatially for operational wildfire simulations and allows re-ignition of the fire. The model is applied within the Spark wildfire modelling framework, a basic example scenario of which is shown in **Figure *1***. Here a point ignition develops into an ellipse under idealised conditions (the colour representing the temperature of the upper bed) and is subject to water suppression applied in a line (the density of which is shown as the vertical grayscale line). The temperature of the upper bed rapidly drops as the water is applied (600 s), extinguishing the fire. However, the amount of water is insufficient to maintain the upper bed below the ignition temperature of the fuel causing reignition (608 s) and a subsequent breakout over the suppression region (700 s). The model is a simplification of the complexities of wildfire combustion and relies on several physical parameters, some of which are difficult to measure and must be estimated. Despite these limitations the model provides a physically based approach to wildfire water suppression which could be used, once fully validated, to inform or direct suppression activities and strategies.

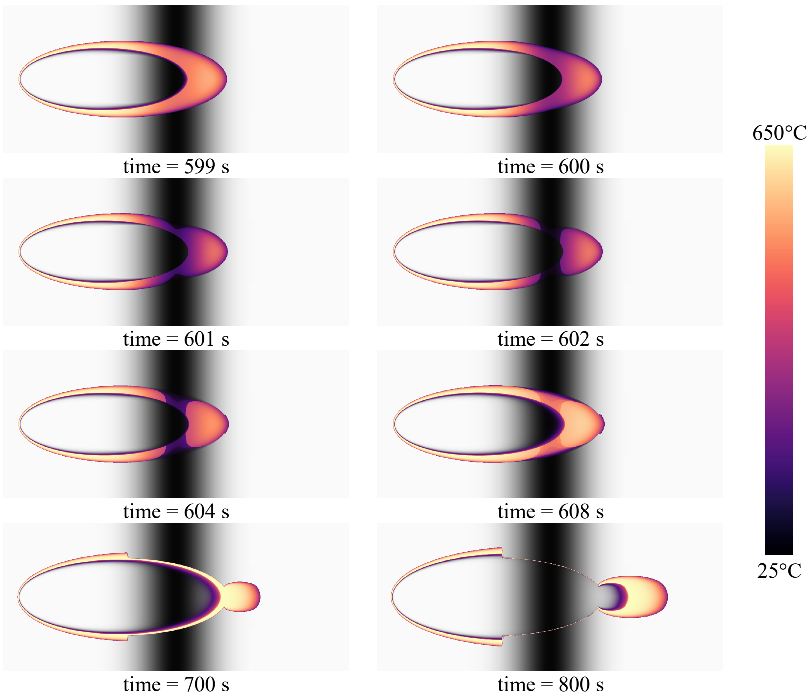

Figure 1. Upper bed temperature for idealized elliptical fire with a fuel density of 12.5 kg m^{-3}. The grayscale shading represents mass of water per unit area from Eq. (8) where black is 1.42 L m^{-2}.

Keywords: *Wildfire modelling, suppression, computational fluid dynamics, Spark*

Stochastic modelling of wind and its implication for wildfire spread predictions

Sahar Masoudian [a], **Jason J. Sharples**[a], **Zlatko Jovanoski**[a], **Simon Watt**[a], **Isaac Towers**[a]

[a]*School of Science, UNSW Canberra, Australia*
Email: s.masoudian@adfa.edu.au

Abstract: Wildfire events have received much attention recently due to their serious socioeconomic impacts in countries like Australia, Canada, the United States and Greece. To tackle wildfire crises, authorities and decision makers rely on a capability to obtain accurate and informative predictions of wildfire spread to support real time decision making, often with life or death consequences.

However, the uncertainty inherent in wildfire model inputs, such as wind speed and direction, makes accurate prediction of wildfire spread a challenging task. To accommodate the inherent uncertainties of the wildfire environment, wildfire modellers are increasingly drawing upon probabilistic or ensemble-based approaches to modelling fire spread. For instance, Cruz [2010] used a Gaussian probability distribution function (PDF), with ensemble members sampled using a Monte Carlo approach, to simulate the variation of wind speed over a range of 27-78 km h^{-1}. In such simulations, spread prediction relies on different probable scenarios rather than a single set of input values. For example, the FireDST framework [French et al., 2014] samples input weather conditions from a uniform distribution, then visualizes the simulator output using burn probability maps, which provide useful information on the likelihood of different parts of the landscape being impacted by fire over a specific period of time [Pinto et al., 2016].

Although ensemble-based approaches can potentially capture the uncertainty in the process of fire modelling, all of the approaches currently in use rely on deterministic simulators to derive burn probability maps. Deterministic simulators provide a single output from a given set of input conditions, and so do not faithfully represent the inherent stochasticity of real fire propagation. In this study, we consider an alternate modelling approach that better acknowledges the intrinsic uncertainties associated with wildfire spread.

Wind speed and direction are critical inputs for bushfire simulation as a significant portion of the uncertainty in the wildfire modelling is caused by spatial and temporal variations in the wind. To capture this uncertainty, one can treat wind speed and direction as stochastic variables; this permits more faithful incorporation of the stochasticity of input variables into the simulation process, and provides a way of obtaining burn probability maps that better reflect the inherent uncertainties of wildfire prediction.

A variety of stochastic processes can be used to model wind speed and direction. While it is still not known which process is the best to use in the context of wildfire simulation, we focused on two that have previously appeared in the wind and fire modelling literature. The Wiener process has used by Zazali et al. [2017] to model fire spread, while the First-Order Gauss-Markov process (also called the Ornstein-Uhlenbeck (OU) process) has received a lot of attention in wind forecasting and for many other environmental factors [Edwards and Hurst, 2001].

In this study, the Wiener and First-Order Gauss-Markov (FOGM) process models are employed to model wind speed and wind direction. The process noise δ of each process is calibrated using a series of data collected from eleven Davis Vantage Pro2 automatic weather stations that were set up at an experimental field site [Quill, 2017]. The wind vector is then simulated by the two stochastic processes using the estimated values of the process noise for each of the two processes. In the final step, we evaluated the models by calculating the root mean square error (RMSE) and the standard deviation of the error (SDE), and compare the distributions of simulated data by stochastic models and the observed data.

Finally, the stochastic wind models were incorporated within the SPARK fire simulation framework [Hilton et al., 2015], to produce representations of fire spread based on stochastic wind fields with the calibrated process noise levels. The outcomes of the stochastic fire spread simulations provided a different interpretation of fire spread compared to simulations based on deterministic ensembles.

Keywords: *Stochastic modelling, wildfire spread, wind, Wiener Process, First Order Gauss-Markov Process*

Pyrogenic potential model calibration from field-scale junction fire experiments

Sahar Masoudian [a,b], Alex Filkov [a,c], Jason J. Sharples [a,b], Trent Penman [a,c], James E. Hilton [a,d]

[a] *Bushfire and Natural Hazards Cooperative Research Centre, East Melbourne, VIC 3002, Australia*
[b] *School of Science, University of New South Wales, Canberra, ACT 2600, Australia*
[c] *School of Ecosystem and Forest Science, University of Melbourne, Creswick, VIC 3363, Australia*
[d] *Data61, CSIRO, Clayton South, VIC 3169, Australia*
Email: alexander.filkov@unimelb.edu.au

Abstract: Understanding the behaviour of junction fires at field-scales is an important problem that has implications for firefighter safety, effectiveness of suppression and extreme wildfire development. This study draws upon data from several field-scale junction fire experiments to calibrate a relatively new dynamic fire propagation model called the 'pyrogenic potential' model (Hilton et al. 2018). We conducted two experimental harvested crop burns in Victoria, Australia, in March and April 2021. A DJI Matrice 210 drone was used to capture high-definition video imagery of fire propagation in synchronisation with sensor data from the on-board Global Positioning System and Inertial Measurement Unit. These sensors enabled the platform/camera orientation and position in space to be aligned with the video footage and the fire propagation georeferenced in GIS software. The georeferenced video file was then used to identify and spatially define fire fronts at set time intervals. As a result, fire progression isochrones were obtained for thirty-two forward junction fire fronts.

The pyrogenic potential model was implemented within the Spark fire simulator framework, which models two-dimensional fire spread using the level set method (Miller et al. 2015). The level set method is coupled with a flow potential model, which represents the fire-induced (pyrogenic) air flow (Hilton et al. 2018). The resulting model is determined by three parameters: u_0, the basic (no-wind) rate of spread dependent on the fuel type; u_1, which describes the influence of wind strength on fire progression; and k, which describes how the strength of the pyrogenic indraft is influenced by the fire's intensity, and hence the strength of pyroconvective interaction between different parts of the fire line. In this study, u_0 is determined from the fuel (assumed to be approximately equivalent to temperate grassland), while the parameters (u_1, k) are considered free.

Fire progression isochrones extracted from the experimental burn data were used to calibrate the pyrogenic potential model. The parameters (u_1, k) were calibrated by maximising the similarity index (Hilton et al. 2018) between the observed and simulated fire progression. Estimates of the parameter k describing the strength of pyroconvective interaction were fairly consistent, with a mean value of 5.6 and a standard deviation of 1.4. The mean value of k =5.6 compared favourably with the value of k =5.4 obtained by Hilton et al. (2018) for a different set of crop fires, indicating consistency of the model across fires with a spatial scale of the order of tens of metres. More experiments using larger fires would be necessary to further examine the scale dependence of this parameter. The results for the wind strength parameter u_1 were a lot more variable, with a mean value of 0.45 and a standard deviation of 0.29. In fact, the estimated wind strength parameter ranged from about 0.1 to 0.8, and while the mean value of 0.45 was similar to the value of 0.58 reported by Hilton et al. (2018), the broad scatter of estimates suggest that this parameter is the more sensitive of the two. However, there are several reasons that could have contributed to the wide range of values found for the wind strength parameter. These include:

- The experimental junction fires studied did not occur in isolation, but as part of the evolution of more complex fire lines. This could have produced additional effects that were not properly accounted for in the simulations (which considered the junction fires in isolation)
- Due to limitations in available resources, the simulations only considered a single wind speed and direction, and did not account for finer variability in the wind field. It is likely that accounting for this variability in the simulations would alter the estimates of the wind strength parameter.

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Keywords: *Pyrogenic potential model, wildfire simulation, fire spread, experimental fires*

Underpinning a new approach to predicting blow-up fire events

R.H.D. McRae [a]

[a]*School of Science, UNSW Canberra, Australia*
Email: r.mcrae@adfa.edu.au

Abstract: Extreme wildfires and their associated blow-up fire events (BUFEs) are rapidly increasingly in their frequency and impacts in eastern Australia and elsewhere. It is becoming essential that predictive capabilities keep up with this. A previously developed model, the Blow-Up Fire Outlook (BUFO) model was based on analyses of case studies of single events or small clusters of events.

During Black Summer, from October 2019 to early February 2020, in eastern Australia over 9 million hectares of forest burnt, with much of that due to extreme wildfire and about a quarter due to BUFEs. Nearly two hundred BUFEs have been identified from that season. The scale of this permitted the acquisition of a database of conditions under which BUFEs did or did not occur, allowing the addressing of selection bias and confirmation bias arising from past reliance on case studies.

The database, Population Ecology of Bushfires during Black Summer (PEBBS) covers six classes of data. PEBBS has some issues concerning completeness and data errors, which are being addressed. Weather observations cover a wide range of fire weather variables, including Drought Factor and pressure patterns, Radiosonde data, based on an archive of skew-T/log-P charts, addresses both the stability profile and key indices. Terrain data covers detailed analytical data describing the terrain and the potential influences on fire behaviour patterns. Near real-time remote sensing data includes imagery from radar, airborne and satellite sensors. Contextual data describes diverse aspects of the climatic dynamics surrounding the activity. Fire data describes classification of fire behaviour indicating the presence or absence of BUFEs or pyroCbs and their interlinkages.

Examples showing the application of PEBBS data are presented covering: pressure patterns; smoke depth; convective caps; and a hotspot transect of a BUFE. PEBBS supports: analysis of regional patterns; percentile rankings; timelines; and fire outcome options. PEBBS is supporting the development of BUFO2, a new version of the BUFO predictive model, that incorporates many new learnings from Black Summer. The PEBBS approach supports both successful incident management and rapid scientific analysis of fires to facilitate learning of lessons.

Keywords: *Blow-up fire event, pyroCb, datasets, Black Summer, prediction*

Modelling terrain for wildfire purposes

R.H.D. McRae [a]

[a]*School of Science, UNSW Canberra, Australia*
Email: r.mcrae@adfa.edu.au

Abstract: Prediction of wildfire behaviour requires data on terrain. Traditionally this involves slope for altering headfire rate of spread, and aspect, which is compared to wind direction to derive overall fire spread vectors. This works well for steady-state wildfires and is embedded in all predictive models in use. Climate change is producing an ever-increasing incidence of extreme wildfires, which couple with the atmosphere above and form blow-up fire events. Some of the principal causes of the coupling require a more detailed analysis of terrain geometry.

This paper is derived from earlier work to develop a predictive model for lightning-ignition-prone lands. For this, Shuttle Radar Topography Mission digital elevation models were used, with a key step being the derivation of the meso-scale elevation residual (MSER), the difference between the elevation and the locally averaged elevation.

In terrain analysis, for any given point of interest, the average, maximum and minimum values within a 1500m radius are derived using desktop GIS packages. The difference between pairs of these values (including the actual elevation) allows estimation of:

- **Landform exposure** (actual minus average, the MSER); high values indicate exposure; low values indicate entrenchment; and near zero values indicate lightning-ignition potential.
- **Landscape ruggedness** (maximum minus minimum); low values (flat) suggest elliptical fires; medium values (undulating) suggest slope affected runs; and high values (rugged) suggest dominance of terrain interactions with the weather.
- **Wind regime** (maximum minus actual) indicate dominant air flows: low values indicate prevailing winds; medium values show lee-eddy winds as well; and high values suggest wind channelling as well.
- **Drainage impairment** (actual minus minimum) indicating potentials for cold air drainage and waterlogged soil.
- **Vorticity-driven lateral spread potential**: can be modelled using first or second derivative of elevation. This is now known to be a cause of many major blow-up events in rugged landscapes.

There is a need to tune the resolution of the digital elevation model in use to the scale of the fire. This requires parameterisation of the local landforms. For example, escalated wildfires in rugged terrain are shown to be relatively insensitive to slope values. The required equations and interpretation of outputs are presented in this paper, along with a worked example.

A proper understanding of both terrain data and the greater insights into fire behaviour that it gives have become essential for keeping ahead of the imperatives caused by the influence of climate change on wildfire risks.

Keywords: *Terrain, vorticity-driven lateral spread, wind regime, lightning ignitions, ruggedness*

Impact of vertically atmospheric phenomena on the atypical fire in mountain valley

Mitsuhiro Ozaki [a], **Rebecca Harris** [a] **Peter Love** [a], **Jagannath Aryal** [b], **Paul Fox-Hughes** [c] **and Grant Williamson** [a]

[a] *School of Geography, Planning, and Spatial Sciences, University of Tasmania*
[b] *School of Electrical, Mechanical and Infrastructure Engineering, University of Melbourne*
[c] *Research and Development Branch, Bureau of Meteorology, Tasmania*
Email: mitsuhiro.ozaki@utas.edu.au

Abstract: Bushfires are not only a natural part of many ecosystems but can also have disastrous consequences for humans in Australia. It is not simple to predict fire behaviour in rugged terrain because fires often propagate contrary to expectations. Even though fire models generally incorporate weather, fuels and topography, which are important factors affecting fire behaviour, they usually only consider surface wind. However, the more elevated wind should be accounted for, in addition to surface winds, when predicting fire spread in rugged terrain because valley winds are often dynamically altered by the interaction of layered atmosphere and topography (Sharples, 2009). Here, fire spread in rugged terrain is examined in a few steps with the Riveaux Road Fire, which was ignited by multiple lightning strikes in the middle of January 2019, southern Tasmania, Australia and burnt approximately $637.19\ km^2$. Firstly, fire propagation is simulated using a new fire simulator (Prototype 2) motivated by the draft specification of the forthcoming new fire danger rating system, the Australian Fire Danger Rating System (AFDRS) (The Australasian Fire and Emergency Service Authorities Council (AFAC), 2020). This prototype was implemented with a Python framework, GeoDjango, with a database management system, PostGIS (Django Software Foundation, 2021; PostGIS Project Steering Project and Project Steering Committee, 2021). The prototype includes the following notable features: (1) embedding several fire spread models, (2) ingesting two resolutions of wind: 1,500 m from BARRA reanalysis and 495 m resampled by Windninja, a diagnostic tool. (3) mapping the prediction polygons of several geometries: Delaunay, Diamond, Hexagon, Square and Voronoi, (4) allowing multiple ignitions at different times and (5) adjusting the rate of fire spread (ROS). This adjustment is necessary because the ROS in each grid is determined by adjacent neighbour grids and the number of grids differs among geometries. For instance, there are approximately 12.5 immediate neighbour grids in Delaunay while there are about 6 neighbours in Voronoi. Where the simulated fire shows the disagreement with observed fire spread, the atmospheric layers are profiled by three methods: comparison of temperature between various atmospheric pressure levels, a skew-T log-P diagram and a cross section above the occurrence point. The skew-T log-P and the cross section are the meteorological functions of the Python library, MetPy (May *et al.*, 2020). Consequently, a divergence was found between the observed and the simulated fire spread in one of the ignitions. There were some weather phenomena above the divergence, such as temperature inversion, high cloud coverage and turbulent winds in upper atmospheric layer. The simulated fire followed the surface winds while the observed fire spread in accordance with the winds in slightly higher altitudes. This suggests that fire prediction requires not only the surface winds but also the higher altitude winds above the surface in rugged terrain.

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Keywords: *Wildfire, rugged terrain, upper air interaction, Metpy, GeoDjango, PostGIS*

Assessing the potential for pyrocumulonimbus occurrence using simple fire weather indices

Jason J. Sharples [a,b] and **Richard H.D. McRae** [a]

[a] *School of Science, University of New South Wales, Canberra, Australia*
[b] *ARC Centre of Excellence for Climate Extremes, UNSW Canberra, ACT, Australia*
Email: j.sharples@adfa.edu.au

Abstract: Pyrocumulonimbus (pyroCb) events occur when a thunderstorm forms within the plume of an active wildfire. These events have received considerable research interest over the last decade, mainly due to an apparent increase in their occurrence and for the fact that they constitute a significant and dangerous escalation in the state of a wildfire. PyroCbs form a subset of the class of extreme wildfires, which are defined by their intense and expansive flaming and the fact that they interact significantly with the surrounding atmosphere, resulting in the development of violent pyroconvection. Extreme wildfires consistently result in the most devastating socioeconomic and environmental impacts.

Researchers have developed several different tools for anticipating elements of pyroCb development, including FireCAPE and the pyroCb firepower threshold. These concepts have proven useful but require data and specialist technical capabilities than may not be readily available to operational personnel; for example, ground crews in Australia typically only have access to forecast surface conditions such as temperature, relative humidity and wind speed, and lower atmospheric conditions such as described by the continuous Haines index, communicated through hourly fire weather updates. Even well-resourced incident management teams may be challenged by the technical demands of implementing such measures.

In this paper we examine the potential of some simple fire weather indices to identify conditions conducive to pyroCb development. We consider the fuel moisture index (FMI), the spread index ($S(\mu)$), the hot-dry-windy index (HDW), and the continuous Haines index (cHaines) and assess their ability to discern instances of pyroCb that occurred during the 2019/20 Australian 'Black Summer'. Specifically, we focus on pyroCbs that occurred in NSW over the three-month period of 1November 2019 – 31 January 2020.

The fuel moisture index and continuous Haines index performed the best at discriminating conditions conducive to pyroCb development: pyroCbs occurred only on days with $FMI < 6$ and cHaines ≥ 8. The spread index and HDW performed less well, possibly because of their incorporation of wind speed, which can actually work against pyroCb development. These results need to be investigated further, because in this initial analysis HDW was only calculated using surface conditions rather than the maximal conditions within a 500-metre layer of the atmosphere, as required by its strict definition. Interestingly, it was also found that, to a very good approximation, HDW is a special case of the spread index; in fact:

$$HDW \approx \frac{82 \max(1, U)}{FMI + 2} = 82\, S(2).$$

Based on the performance of the simple indices, a novel index, $\mathcal{P}$, was defined as the quotient of the continuous Haines index and the fuel moisture index:

$$\mathcal{P} = \frac{\text{cHaines}}{FMI}.$$

It was found that pyroCb occurrence was strongly associated with days for which $\mathcal{P} \geq 2$; that is, when the continuous Haines index was twice the fuel moisture index, or more.

The results presented here provide a parsimonious way for operational personnel to gauge the likelihood of pyroCb occurrence based on readily available daily forecast fire weather information. It is likely that these concepts can also be applied at finer temporal scales. Fire weather variables such as temperature and relative humidity (which can be easily combined to give FMI) and cHaines are routinely available in operational fire weather reports, and so "cHaines $\geq 2 \times FMI$" provides a useful rule of thumb for assessing the likelihood of dangerous escalations in wildfire activity.

Keywords: *Simple indices, fire weather, pyrocumulonimbus, model parsimony*

Incorporating directionality in the modelling of firebreaks using a two-dimensional dynamic fire spread simulator

William Swedosh [a] **and James Hilton** [b]

[a] *Land & Water, CSIRO, Clayton, VIC 3168, Australia*
[b] *Data61, CSIRO, Clayton, VIC 3168, Australia*
Email: Will.Swedosh@csiro.au

Abstract: Accurate predictions of wildfires are necessary for planning and operational fire management applications. While operational predictive models are aimed at capturing the effect of weather, vegetation and topography on fire spread, the understanding and incorporation of disruptions in the landscape such as firebreaks, roads and rivers are less understood. Developing and implementing models that capture the effect of disruptions on the spread of fires in the landscape is likely to lead to more accurate predictions of fire spread.

Studies have shown that the probability of fires crossing firebreaks depends on factors such as the fire behaviour, the width of the disruption and type and condition of the vegetation the fire is burning through. While computational fluid dynamics models show some promise at simulating breaching firebreaks, they are quite complicated and too slow to be included in operational predictions. Empirical models are far simpler and are much more suitable for fast simulations.

In this study we implement an empirical firebreak breaching model using the Spark wildfire simulator. We extend the model to include local fireline intensity and the wind direction relative to disruption using an effective width implementation. We also develop and utilise a method to include wind bearing fluctuations in the simulations.

We tested our implementation against the empirical model for fires approaching firebreaks of varying widths. There was complete agreement between the empirical model and whether or not the firebreak was breached in the simulation. We then tested the effective width implementation with simulations of fires approaching a firebreak at different angles. Again, there was complete agreement between the result from the empirical model and the fire simulation on what approach angle was required to stop the fire breaching the firebreak due to an increasing effective firebreak width.

We then conducted simulations for more realistic scenarios using a road network as the firebreak where the road network had sections at different angles to the firebreak. The simulation results showed differences in behaviour with road orientation, with head on approaches able to breach the road, while some sufficiently angled roads were unable to be breached. Wind fluctuations were included in the final simulation, which allowed the fire to cross the road in more locations than before.

We intend to build upon the methods developed here so that more realistic firebreak breaching can be modelled in operational simulations in the future.

Keywords: *Wildfire, modelling, firebreak, disruption*

Improvement of drag model for non-burning firebrand transport in Fire Dynamics Simulator

Rahul Wadhwani [a,b], Duncan Sutherland [a,b,c], Graham Thorpe [d] and Khalid A Moinuddin [a,b]

[a] *Centre for Environmental Safety and Risk Engineering, Victoria University, Melbourne, Australia*
[b] *Bushfire and Natural Hazards CRC, Melbourne, Australia*
[c] *School of Science, University of New South Wales, Canberra, Australia*
[d] *College of Engineering and Science, Victoria University, Melbourne, Australia*
Email: khalid.moinuddin@vu.edu.au

Abstract: Firebrands play a crucial role in increasing the severity of wildfires by driving fire growth, damaging structures, and starting new fires. Predicting the transport of firebrands and their propensity to ignite new fires is of significant interest to fire communities. Developing an operational firebrand transport sub-model from the field studies is cumbersome, expensive, and has significant associated risks to equipment, community and firefighters. Physics-based models have the potential to assist in the development of such firebrand transport sub-models which can be utilised to improve the efficacy of existing operational fire models. The present study showcases one of the initial works carried out in the development of such a physics-based firebrand model. The work utilises Fire Dynamics Simulator (FDS), a commonly used open-source physics-based fire model. The Lagrangian particle sub-model of FDS is used to simulate the transport of firebrand particles. The Lagrangian sub-model is generally used to model the transport of droplets and mist and has been extensively validated. However, the validation of this sub-model for the transport of solid particles such as firebrands is limited. The issue is exacerbated when particles are of a non-spherical shape and can undergo complex reactions over their transport such as burning.

In this work, we utilise a firebrand generator prototype that produces a uniform Lagrangian shower of non-burning idealised firebrands. A set of in-house experiments are conducted to study the transport of three isometric shapes of non-burning firebrands i.e. cubiform, cylindrical and square-disc. These sets of experiments are used to quantify the efficacy of the inbuilt particle drag model of FDS and suggest potential alternative drag models that can be employed without loss of computational speed, major amendment in the fire model, are applicable to a wide range of particles shapes, and potentially improved prediction. In general, it is found that the suggested alternative Haider and Levenspiel drag model improves the estimation of firebrand distribution in terms of peak location, maximum and minimum longitudinal distribution with exception to cubiform particles for peak location. The exception is mainly due to inherent error association with the alternative drag model in overestimating the drag coefficient. For other situations, Haider and Levenspiel drag model shows either an improvement or stays the same. However, the study found that the existing point particle assumption to represent particles in FDS is not suited to estimate the lateral spread of firebrands especially when the secondary motion of a particle on its axis is involved such as cylindrical and square-disc particles. Our studies found, the lateral spread is found to be in the range of ~5-15% thinner compared to its experimental width for cylindrical particle distribution. For the square disc, it is not possible to quantify such differences due to the computational limit associated with our present study. It can be qualitatively suggested that it is found to be more than cylindrical particles. A further set of experiments and their numerical validation is required to ascertain the above finding, especially with different sizes, isometric and non-isometric shape, the speed of firebrand particles and burning process to establish the efficacy of a particular drag model for firebrand transport.

Keywords: *Fire Dynamics Simulator (FDS), firebrand particles, Lagrangian particle, firebrand generator, drag models*

Application of neural networks to rate of spread estimation in shrublands

Rahul Wadhwani [a], Duncan Sutherland [b], Khalid A. Moinuddin [a] and Jason J. Sharples [b]

[a] *Centre for Environmental Safety and Risk Engineering, Victoria University, Melbourne, Australia*
[b] *School of Science, University of New South Wales, Canberra, Australia*
Email: duncan.sutherland@adfa.edu.au

Abstract: Wildfire behaviour prediction is a complex and challenging endeavour that incorporates information relating to various factors such as vegetation, local and ambient weather conditions, and topography within a particular modelling framework. Often, a single model cannot provide a complete description of the phenomenon due to significant differences in the temporal and spatial frames required to resolve the relevant physical process. The low computational cost and simplified nature, statistical-based models of fire spread are an obvious choice for operational purposes. However, most statistical regression models of rate of spread still possess significant degrees of uncertainties. Despite considerable progress in modelling fire behaviour, fires can still create unexpected scenarios for emergency services personnel during real situations, and result in loss of containment, significant injury, or even fatalities. Recently, there has been significant interest in utilising machine learning techniques to better predict wildfire for improved management of forests and parks. The present work uses an artificial neural network to estimate the rate of fire spread in shrubland. The model is trained upon data from the published literature to establish a non-linear relation between the rate of fire spread and twelve input variables, namely: vegetation height, vegetation cover, fine dead and live fuel load, air temperature, relative humidity, wind speed at 2 m height, slope, moisture content of dead and live fuel, and ignition length. The network model-based estimates of the rate of fire spread yield results close to the measured data, with a correlation coefficient r^2=0.87. Furthermore, the model was able to quantify the significance of all input variables on rate of fire spread. This capability of neural network model can be helpful in determining how much a factor contribute to rate of fire spread which otherwise be overshadowed by the assumptions involved in a regression model. For this dataset, the moisture content of dead fuel, wind speed at 2 m height, and vegetation height were the most significant variables for determining the rate of fire spread in shrublands. This agrees with other statistical regression model studies in the literature. The neural network model was also able to quantify the dependency on ignition line length a variable that was deemed insignificant by the existing regression model. This preliminary study provides a benchmark for further application of neural networks and other machine learning techniques to model wildfire rate of spread. Further work could also involve testing the predictive capability of the neural network model on other independent datasets pertaining to shrubland fires and its extension to other fuel types.

Keywords: *Artificial neural network (ANN), machine learning, fire spread, shrubland*

Coupling vapour and capillary fluxes from the soil to predict surface fuel moisture content

L. Zhao[a,b] **and M. Yebra**[a,b,c]

[a] *Fenner School of Environment and Society, The Australian National University, Canberra, Australia*
[b] *Bushfire and Natural Hazards Cooperative Research Centre, Melbourne, Australia*
[c] *Research School of Aerospace, Mechanical and Environmental Engineering, The Australian National University, Canberra, Australia*
Email: li.zhao@anu.edu.au

Abstract: The fuel moisture content (FMC) of the surface fuel (i.e., litter fuel) plays a decisive role in fire ignition and fire danger rating systems. Therefore, accurate predictions of litter FMC is beneficial to evaluate fire risks and manage forest ecosystems. Litter FMC mainly changes in response to meteorological factors and models often describe litter FMC as complex mathematical equations of temperature and air humidity. Soil moisture content has also been proposed to affect litter FMC due to evaporation and capillary from the soil. Our previous research showed that litter FMC prediction was improved when vapour flux from the soil to litter was included in a physics-based model. However, rather few models involve soil water content when predicting litter FMC, and to our knowledge, no modes have included capillary flux from the soil in the forecast of litter FMC. This research aimed to evaluate whether litter FMC predictions can be improved by incorporating the hydrological process (i.e., capillary flow) at the soil-litter interface and explore the possible role of soil moisture in litter FMC simulations. In this study, we coupled soil moisture in the physics-based litter FMC prediction model (Koba; Matthews, 2006), involving both vapour and capillary fluxes from the soil. The coupling of vapour exchange between the soil and litter was quantified by the evaporation from the topsoil (Zhao et al., 2021), whereas the incorporated capillary flux from the soil was quantified based on Darcy's equation in the unsaturated flow. The coupled models were tested at a dry and wet site in the Australian National Botanic Gardens, Canberra where litter FMC observations were measured using automated fuel stick sensors and meteorological variables (temperature, relative humidity, wind speed, rainfall, radiation and soil moisture) were made from in-situ observations. Three versions of models were compared against observations for 2019-2021: 1) uncoupled Koba model; 2) coupled Koba model that only accounts for vapour flux from the soil and; 3) coupled Koba model that incorporates both vapour and capillary fluxes from the soil. Results show that the three models showed similar performances over the dry days at the dry site, when the soil was also very dry. However, both models without capillary flux from the soil (i.e., the uncoupled Koba model and the coupled Koba model that only accounts for vapour flux from the soil) tend to under-estimate litter FMC over the wet days when the soil water content was high, whereas the coupled Koba model incorporated both vapour and capillary fluxes from the soil improved the underestimations of litter FMC and showed the best performance. This was more noticeable at the wet site. Simulation results suggest that soil plays a determinant role in litter FMC simulations due to evaporation and capillary flow from the soil, particularly under wet soil conditions. The contribution of moisture from the soil to litter is more likely to be ignored over a long-term drying period in summer but more noticeable over wet days. Further research involves evaluating the coupled model under various environmental conditions, which has implications for forest fire forecast and management at a large scale.

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Keywords: *Fuel moisture content, forecast, coupling model, soil moisture, capillary flow*

Tropical cyclone-induced extreme winds in climate datasets: East coast of Australia

S. S. Bell[a,b], **S. S. Chand**[b], **A. J. Dowdy**[a], **H. A. Ramsay**[c], **A. Deo**[b], **C-H Su**[a], **A. Brown**[a] **and H. Ye**[a]

[a] *Bureau of Meteorology, Docklands, Australia,* [b] *School of Engineering, IT and Physical Sciences, Federation University Australia* [c]*CSIRO Oceans and Atmosphere, Aspendale, Australia*
Email: samuel.bell@bom.gov.au

Abstract: Extreme wind speeds, which are typically induced by tropical cyclones (TCs) in coastal regions of tropical Australia, are an important hazard to consider in the context of climate change. Here, a range of climate datasets based on direct observations, reanalyses and regional climate model simulations are used to examine trends in TC-related extreme winds over coastal Eastern Australia. Wind gust speed estimates from best-track data and automatic weather station (AWS) observations are used to calibrate reanalysis wind gusts from the Bureau of Meteorology (BoM) Atmospheric high-resolution Regional Reanalysis for Australia (BARRA) and from the global ERA5 reanalysis. Together, these different datasets provide complementary lines of evidence in relation to historical changes in extreme wind gust speeds.

Differences between the occurrence frequency of TC-related wind gusts reaching Category 4/5 on the Australian TC intensity scale and the return periods of TC-related wind gusts over three decades (1990–2019) are presented. Lognormal and Weibull curves are fitted to the extreme value wind speeds and used to provide estimates of associated return periods. Results indicate that the East coast has likely experienced a slightly increased frequency of extreme wind gusts from TCs over the more recent time period (2005–2019), noting considerable uncertainties around these extremes given the limitations of the available data, including that of rapidly evolving observational practices and short time period.

Projection results from climate models provide can provide a more homogenous evaluation of the impacts of climate change over a longer time period than is currently available, despite having their own limitations such as model biases and inaccurate representation of certain climate processes. The same experimental methods applied to the observational datasets, are here applied to future projections based on several regional climate model (RCM) simulations under high emission scenarios: NSW and ACT Regional Climate Modelling (NARCliM), CSIRO Conformal Cubic Atmospheric Model (CCAM) and BoM's Atmospheric Regional Projections for Australia (BARPA). NARCliM results are downscaled from a selection CMIP3 models and use a mean wind speed rather than a gust, while CCAM and BARPA results are downscaled from a selection of CMIP5 models. Results from these projections on extreme wind speeds are generally inconclusive for climate trends on the East coast but indicated that an increase in intensity would be more likely than a decrease in a warmer world.

Small sample size and considerable interannual variability in landfalling severe TCs means that there are considerable uncertainties around long-term observed trends in their occurrence. However, a small increase in the observed occurrence frequency of severe TCs for the East coast is noted here based on observations, such that an increase in the more damaging wind gust speeds associated with severe TCs (i.e., rare events with higher return period values) is a plausible outcome for the future climate of Eastern Australia. For example, the return period projections from the regional climate models generally suggest an increase is more likely than a decrease for the most extreme wind gust speeds. We note that whether a change in long-term return periods of wind gusts or a change in the frequency of TC landfalls of any intensity is more important is likely specific to the region or application being considered. Although there are considerable uncertainties around this topic of extreme wind gusts and TCs in a changing climate, our findings are intended to help contribute to the range of guidance available in relation to managing climate risk in Eastern Australia.

Keywords: *Reanalysis, climate model, regional downscaling, tropical cyclones, wind speed return periods*

Interacting climate modes modulate the supply of moisture for east Australian rainfall

C. Holgate[a,b], J. Evans[b,c], A. Taschetto[b,c], A. Sen Gupta[b,c] and A. Santoso[b,c,d]

[a]Fenner School of Environment and Society, Australian National University, Canberra, Australia [b]ARC Centre of Excellence for Climate Extremes, University of New South Wales, Sydney, Australia [c]Climate Change Research Centre, University of New South Wales, Sydney, Australia [d]Centre for Southern Hemisphere Oceans Research, CSIRO Oceans and Atmosphere, Hobart, Australia
Email: chiara.holgate@bom.gov.au

Abstract: Modes of variability such as the El Nino Southern Oscillation (ENSO), Indian Ocean Dipole (IOD) and Southern Annular Mode (SAM) can drive important changes to the east Australian climate affecting extremes such as droughts, floods and bushfires. The importance of forecasting these extremes and their expected future changes motivates a deeper understanding of the physical link between these modes of variability and regional rainfall.

To provide a new perspective on the physical links between large-scale climate modes and regional rainfall, we analyse how modes of variability modify the supply of moisture for winter-spring rainfall events. Rainfall anomalies can arise due to changes in the typical supply of moisture via altered marine or terrestrial evaporation rates (a large-scale thermodynamic response); or, evaporation rates may remain largely unchanged but the contributing moisture is redirected elsewhere due to circulation shifts (a dynamic response); or, the supply of moisture to a region remains largely unchanged but local conditions are not conducive to the precipitation of that moisture (a local thermodynamic response).

To distinguish between these processes, we used a Lagrangian back-trajectory model to identify regions of anomalous moisture supply, together with anomalies of evaporation, total precipitable water and 500 hPa vertical wind speed. The back-trajectory model traced the path of moisture supplying rainfall events backwards in time and space to identify its evaporative origin. Moisture supplying all rainfall events (>2 mm day^{-1}) between 1979 and 2013 was tracked, yielding daily maps of evaporative sources contributing to rainfall in the east Australian region. We then computed monthly moisture source anomalies from the 35-year climatology to analyse the changes during each climate mode phase.

Our analysis revealed that during standalone La Nina events, dynamic changes to moisture transport were associated with both increased precipitable water and enhanced ascending motion that facilitated local thermodynamic precipitation-generating processes, which together led to above-average precipitation. On the other hand, below-average precipitation during standalone El Nino events was associated with strongly enhanced subsidence. These processes were often more pronounced when La Nina co-occurred with negative IOD or positive SAM periods, and when El Nino co-occurred with positive IOD or negative SAM periods.

Keywords: *Back-trajectory, moisture source, climate modes, ENSO*

EXTENDED ABSTRACT ONLY

Bias correction of climate projections for bushfire hazard mapping

Durga L. Shrestha [a], **David Robertson** [a], **Yong Song** [a], **Alessio Arena** [b], **Ben Leighton** [a], **Will Swedosh** [a], **Kimberley Opie** [a], **Justin Leonard** [a]

[a] *CSIRO Land and Water, Clayton, VIC 3168, Australia*
[b] *CSIRO Land and Water, Dutton Park, QLD 4102, Australia*
Email: durgalal.shrestha@csiro.au

Abstract: National Bushfire Intelligence Capability (NBIC) and state departments such as the WA Department of Planning, Land and Heritage are generating Bushfire Prone Areas Mapping to inform bushfire planning responses. Fire hazard is assessed using fire behaviour models that consider the potential fuel load, site characteristics (such as slope) and fire weather potential. For historical analysis, the fire weather potential is derived from hourly ERA5 reanalysis data (Hersbach et al., 2020). Recent bushfires in New South Wales and Victoria show that climate change is expected to modify the fire weather potential (e.g. fire seasons to start earlier, end later and involve more frequent extremes of weather) and therefore for planning purposes there is a need to understand future fire hazard and how it may be influenced by future fire weather potential. Projections of climate change are readily available from national and international (e.g., the coupled model intercomparison project phase 5, CMIP5) global climate models (GCMs). The distribution (mean, variance, sequencing) of model projections from GCMs can be considerably different to the distribution of observations for historical periods. Projections of climate change are available at coarse spatial resolution (100 to 300 km), but bushfire mapping and other applications require much finer resolution. Therefore, it is common practice to apply bias corrections to finer resolution historical data to adjust for these distributional differences.

In this presentation we describe the bias correction methods for climate projections, particularly three key weather inputs - temperature, precipitation and dew point, to the fire behaviour models. We apply two bias correction methods, namely delta correction and quantile mapping. Delta correction methods adjust historical observation data (such as ERA5) based on change signal from the GCMs. The change signal is derived from difference (additive, multiplicative) between a future scenario and the historical GCM run. Quantile mapping also adjusts historical observations, but unlike delta correction where changes are made to the magnitude of the data, it corrects distribution of historical observation. The bias correction methods we use in this study provides corrected observation of a long record (40 years) of high spatial-temporal resolution that looks like future climate projections, which is crucial for extreme value analysis of bushfire.

The bias corrected methods are applied to climate projections from 11 CMIP5 (Taylor et al., 2012) models and two representative concentrations pathways (RCP4.5 and RCP4.5). The bias correction methods are applied separately for two 20-year future periods, near term (2026 to 2045) and long term (2080 to 2100) across Western Australia. We use ERA5 reanalysis data as the reference set of observations for the historical period. Then we derive key inputs to fire behaviour model such as McArthur drought factor (McArthur, 1967) from bias corrected climate projections. We compare McArthur drought factor from 11 GCMs for two climate change scenarios, including two future periods against that from historical observation. The uncertainty of the climate projections and derived key inputs to the fire behaviour model is also assessed. The preliminary results show that the risk of bushfire is likely to increase under different climate change scenarios.

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Keywords: *Climate change, CMIP5, ERA5, Bias correction, Bushfire hazard*

Evaluation of soil moisture products to monitor drought in southeast Australia

Q. Zhu[a], A. Clark[a], J. B. Wurtzel[a] and K. Broadfoot[a]

[a] *Orange Agricultural Institute, Climate Branch, NSW Department of Primary Industries, Orange, New South Wales 2800, Australia*
Email: esther.zhu@dpi.nsw.gov.au

Abstract: Soil moisture plays a crucial role in both climate and agricultural systems. It regulates land surface energy and the water fluxes which underpin drought and flooding processes, as well as providing feedback to the climate system. As one of the main determinants of pasture and crop growth, soil moisture is also a key driver of agricultural yield. Drought monitoring based on soil moisture has been limited at the regional to farm scale due to the lack of high precision, long sequence soil moisture observation data. In the last two decades, the use of various automated sensing field technologies along with the development of microwave remote sensing, have made accurately monitoring of soil moisture at regional level possible.

As part of its role in monitoring seasonal conditions during the 2017-2020 drought, NSW DPI used a soil water balance driven by data from the Australian Water Availability Program that was calibrated for fluxes occurring at pasture and crop rooting depth. As part of the Enhanced Drought Information System (EDIS), this methodology proved useful for state-wide and large region assessments. However, to meet the needs of industry in the new Future Ready Regions EDIS development program, a more precise regionally comprehensive but farm to paddock level water balance is required. In this paper, we take the first step developing this new soil water monitoring framework by evaluating three soil moisture profile products. This included the original EDIS water balance as well as remotely sensed 3-day root-zone soil moisture from Soil Moisture Active Passive (SMAP), and modelled soil moisture from Australian Water Resource Assessment Landscape (AWRA-L) developed by CSIRO and BoM. Each approach has its own strengths and limitations for monitoring farm to paddock level soil moisture for agriculture. Overall, soil moisture from EDIS is the most sensitive to individual rainfall events compared to the soil moisture from AWRA-L and SMAP. The AWRA-L soil moisture field is greatly affected by topographic factors; this may be because the key static parameters are calibrated via catchment streamflow. SMAP was found to captures seasonal variation and extreme weather well, but was limited by its spatial resolution at 9km, especially in Western NSW where there are inadequate in situ observations.

In conclusion, it is recommended that enhancements to soil moisture for monitoring at farm to paddock scale monitoring can be made by blending remote sensing, biophysical models and ground-based agricultural sensor networks in a robust data assimilation framework.

Keywords: *Soil moisture, drought monitoring, microwave remote sensing, EDIS*

From offshore to onshore probabilistic tsunami hazard assessment: Efficient Monte-Carlo sampling

G. Davies[1]

[1]*Place, Space and Communities Division, Geoscience Australia, ACT, Australia.*
Email: gareth.davies@ga.gov.au

Abstract: Tsunami inundation is rare on most coastlines, but large events can have devastating consequences for life and infrastructure. There is demand for inundation hazard maps to guide risk-management actions, such as the design of tsunami evacuation zones, tsunami-resilient infrastructure, and insurance. But the frequency of tsunami-generating processes (e.g., large earthquakes, landslides, and volcanic collapses) is highly uncertain. This reflects limitations in scientific knowledge, and the short duration of historical records compared to the long average time between dangerous tsunamis. Consequently, tsunami hazards are subject to large uncertainties which should be clearly communicated to inform risk-management decisions.

Probabilistic Tsunami Hazard Assessment (PTHA) offers a structured approach to quantifying tsunami hazards and the associated uncertainties, while integrating data, models, and expert opinion. For earthquake-generated tsunamis, several national and global-scale PTHAs provide databases of hypothetical scenarios, scenario occurrence-rates and their uncertainties. Because these “offshore PTHAs” represent the coast at coarse spatial resolutions (~ 1-2 km) they are not directly suitable for onshore risk management and can only simulate tsunami waveforms accurately in deep-water, far from the coast. Yet because offshore PTHAs can use earthquake and tsunami data at global scales, they offer relatively well tested representations of earthquake-tsunami sources, occurrence-rates, and uncertainties. Furthermore, by combining an offshore PTHA with a high-resolution coastal inundation model, the resulting onshore tsunami hazard can in-principle be derived at spatial resolutions appropriate for risk management (~ 10 m) for any site of interest.

This study considers the computational problem of rigorously transforming offshore PTHAs into site-specific onshore PTHAs. In theory this can be done by using a high-resolution hydrodynamic model to simulate inundation for every scenario in the offshore PTHA. In practice this is computationally prohibitive, because modern offshore PTHAs contain too many scenarios (on the order of 1 million) and inundation models are computationally demanding. Monte-Carlo sampling offers a rigorous alternative that requires less computation, because inundation simulations are only required for a random subset of scenarios. It is also known to converge to the correct solution as the number of scenarios is increased.

This study develops several approaches to reduce Monte-Carlo errors at the onshore site of interest, for a given computational cost. As compared to existing Monte-Carlo approaches for offshore-to-onshore PTHA, the key novel idea is to use deep-water tsunami wave heights (from the offshore PTHA) to estimate the relative “importance” of each scenario near the onshore site of interest, prior to inundation simulation. Scenarios are randomly sampled in a way that over-represents the “important” scenarios, and the theory of importance sampling enables weighting these scenarios to correct for the sampling bias. This can greatly reduce Monte-Carlo errors for a given sampling effort. In addition, because importance-sampling is analytically tractable, the variance of the Monte-Carlo errors can be estimated at offshore sites prior to sampling. This helps modellers to estimate the adequacy of a proposed Monte-Carlo sampling scheme prior to expensive inundation computation. The theory of optimal-sampling can also applied in a way that to reduces the analytical variance of the Monte-Carlo errors, by non-uniformly sampling from earthquakes of different magnitudes.

The new techniques are applied to an onshore earthquake-tsunami PTHA in Tongatapu, the main island of Tonga. In combination the new techniques lead to efficiency improvements equivalent to simulating 4-18 times more scenarios, as compared with commonly used Monte-Carlo methods for onshore PTHA. They also enable the hazard uncertainties in the offshore PTHA to be translated onshore, where they are of most significance to risk management decision-making. The greatest accuracy improvements occur for large tsunamis, and for computations that represent uncertainties in the hazard.

Keywords: *Tsunami hazard assessment, Monte-Carlo sampling, importance sampling*

Urban Land Use Land Cover extraction for catchment modelling using deep learning techniques

Siming Gong, **James Ball and Nicholas Surawski**

[a] *School of Civil & Environmental Engineering, University of Technology, Sydney, 2007, Australia*
Email: siming.gong@student.uts.edu.au

Abstract: Interaction between humans and floods usually requires management in a risk context. Effectiveness of flood management plans is undermined by limitations on available data. Catchment modelling is a practical approach to expand available data for forecasting design flood quantiles. When dealing with urban catchments, with their complex land use land cover (LULC) and limited monitoring data, catchment modelling is needed (Ball et al., 2019). The heterogeneity of LULC plays a critical role in rainfall-runoff (RR) processes within urban catchments. Obtaining LULC from remote sensing imagery of urban catchments for modelling purposes is becoming increasingly important as the variability and diversity of land uses occurred during urban development. Deep Learning Neural Networks (DNNs) can achieve image classification and segmentation together with a powerful capacity to process complex workflow and features, to learn sophisticated relationships, and to produce outcomes in many fields. Numerous DNNs based techniques have been developed to classify and extract features of remote sensing imagery at pixel scale (Zhang et al., 2016). However, DNNs techniques for LULC parameterisation for catchment modelling of urban catchment remain undefined.

Three approaches, Unet, DeepLabV3+ and MeanShift+Unet, were proposed for generating a pixel-based LULC classification and semantic segmentation for the Alexandria Canal catchment in Sydney, Australia. Unet and DeepLabV3+ are DNNs based computer vision (CV) tools for pixel classification, while MeanShift is a clustering algorithm for extracting spatial features with similar spectral and texture information. Additionally, applicability of their outputs as inputs to different catchment modelling systems was investigated. The first step was to georeference catchment imagery followed by training sample generation; LULC classes were defined as tree, railway, water body, pervious, road, impervious and roof. Preliminary segmentation was conducted using Meanshift on the raw image, and then both Unet and DeepLabV3+ were trained on the raw image. The sample also trained Unet on the MeanShift segmentation output. After training, the entire image was used to test the three methods. A confusion matrix was used to assess LULC segmentation by comparing ground truth and classification results for 500 points.

Using confusion matrices, all three methods achieved excellent classification and segmentation with mean accuracies of 83.6%, 81.03% and 83.79% for Unet, DeepLabV3+ and MeanShift+Unet, respectively. MeanShift+Unet achieved the highest consistency but a lower accuracy in some LULC classes. A simplified LULC class schema that merged sub-classes with impervious area RR response (railway, road, impervious, roof) was tested also. The merge of LULCs resulted in impervious area identification accuracy increasing significantly, the MeanShift+Unet achieved the highest accuracy of 98.47%. Full-distributed modelling systems like TUFLOW require a detailed LULC class schema to represent spatial features and need high geometric accuracy of LULC segmentation at a pixel scale to simulate RR process of a catchment. Semi-distributed modelling systems like EPA-SWMM simulate RR process at subcatchment scale and are more flexible in spatial geometric accuracy and require fewer LULC parameters than the fully-distributed modelling systems. Consideration of these results shows that DNNs are suitable for semi-distributed models, but need further development for fully distributed models.

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Keywords: *Catchment modelling, Land use Land cover (LULC), remote sensing, DNNs, Confusion Matrix*

Modelling the impacts of bushfire on flood frequency and catchment sediment load

Fazlul Karim [a], **Tapas K. Biswas**[a], **Alex Sims**[b] **and Klaus Joehnk**[a]

[a] *CSIRO Land & Water, Canberra, Australian Capital Territory*
[b]*Alluvium Consulting, Cremorne, Melbourne, Victoria*
Email: fazlul.karim@csiro.au

Abstract: Bushfires strongly influence hydrological processes in natural catchments. This paper examines the impact of the 2019-20 Black Summer bushfire on flood risk in the Tuross River catchment in southeast NSW. About 68% of the 1808 km^2 catchment area was burned causing serious environmental concern in the region. The study was conducted using the XP-RAFTS hydrological model which uses a node-link approach for runoff simulation and routing (Innovyze, 2016). Flood prevalence was estimated using the Log-Pearson Type-III probability distribution function.

Results showed a large increase in both post-fire mean annual flow (MAF) and peak flow (also called flood flow). The increase in MAF is in the range of 7 to 12% for the 1st year, 1 to 5% in the 2nd year and about 1% in the 5th year. However, the impacts on peak flow are much higher compared to MAF, increasing by as much as 30%. A possible explanation for large peak flow is faster catchment runoff because of low surface resistance due to reduced vegetation cover. This has immediate consequence on flood frequency as the post-fire peak flow volume increases following any storm event. Fig. 1 shows an example of changes in post-fire flood for the Tuross River catchment. For the post-fire condition, peak discharge increased for all return periods, but this increase was greatest for larger (>20yr ARI) flood events. The net impact is a decreased return period (i.e. the event occurs more frequently) for a given discharge. For example, the return period of a 20-year pre-fire flood (~1500 m^3/s) reduces to approximately 15-year post-fire, and a 10-year pre-fire flood (~1,000 m^3/s) reduces to approximately 8-year flood. As seen previously changes are higher for the rarer events.

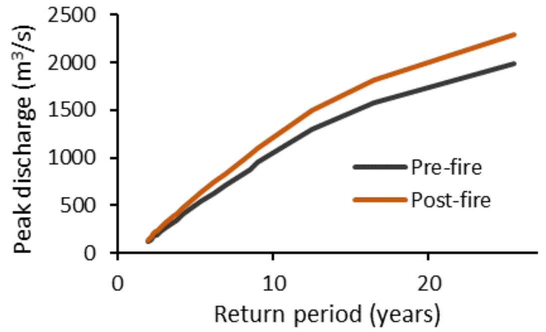

Figure 1. Comparison between pre- and post-fire floods

The heavy rain falling on burnt bare soil can also lead to serious erosion and high sediment export from the catchment. We calculated fine sediment export by using Revised Universal Soil Loss Equation (RUSLE) derived estimate of erosion rate coupled with a sediment delivery ratio (SDR). The total fine sediment exported from hillslopes to the downstream streams was estimated on a subcatchment basis by multiplying gross erosion rate, area of subcatchment and the hillslope SDR. Estimated annual post-fire sediment loads were 30 to 40 times higher than the pre-fire condition for the first year. As the bulk of sediment is transported during post-fire high flow events, the increase in river sediment loads immediately after post-fire floods is much higher than the more subtle increase in mean annual sediment loads. As the catchment vegetation regenerates, both peak and annual sediment loads rapidly decline within 2 years of the fire.

This study provided useful information on flood risk sediment load associated with a bushfire in the Tuross river catchment. There are several factors that influence the immediate post-fire increase in runoff, but the main factors are reduced interception and infiltration. Moreover, reduced surface vegetation produces less resistance to flow and thus produces higher flood peaks.

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Keywords: *Bushfire, hydrological model, catchment flood, sediment load*

INVITED PAPER

EXTENDED ABSTRACT ONLY

2D hydrodynamic modelling for the Cooper Creek Floodplain

Cherry May Mateo[a], Jai Vaze[a], Russell Crosbie[a], Shaun Kim[a], Steve Marvanek[a], and Catherine Ticehurst[a]

[a]*Commonwealth Scientific and Industrial Research Organisation, Land and Water, Australia*
Email: cherry.mateo@csiro.au

Abstract: The Cooper Creek floodplain has a complex network of intermittent and anastomosing channels that flood frequently. These floods are necessary to replenish hundreds of waterholes and wetlands that are critical ecological assets. However, extreme floods in the region can be catastrophic to gas resource development and agricultural production. While infrastructure could be built to protect the gas resources and agricultural areas, such structural changes might lead to blockages or changes in the connectivity of the intricate network of rivers and wetlands (Holland et al., 2021). To quantify flood inundation across the floodplain under current and future development scenarios, we have developed hydrodynamic models for Cooper Creek.

The 2D MIKE 21 Flexible Mesh (MIKE21FM) model was used to develop flood inundation models for the two sections of the Cooper Creek – the Queensland section (22,983 km^2) and the South Australia section (8,636km^2). A 1m LiDAR DEM data stitched-in with waterhole bathymetry information from survey data was used to capture the topographical details in the floodplain. The following inputs were also used to develop the models: flow data from observation gauges, ungauged flow data from Sacramento model outputs, climate data from AWAP, Landsat-derived water extent data, land use data, and soil characteristics data. The MIKE21FM models were calibrated using more frequent 1 in 2 and 1 in 5-year events in both modelling sections. Modelling smaller but frequent events are critical to ensure that water is replenished in the ecological assets.

The simulated inundated extents show good agreement with those of the Landsat images (Vaze et al., 2021). Reasonably good agreement in simulated and Landsat inundation extents was also obtained when the models were used to validate 1 in 10-year flood events. Such events flood most of the floodplain. These results indicate that the models can be instrumental in analysing a wide range of events and future development scenarios. With appropriate modifications, the existing models can be used in quantifying and assessing the impacts of future climate, environmental, and structural changes in the floodplain.

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Keywords: *Cooper Creek, MIKE21 Flexible Mesh, floodplain inundation modelling*

Two-monthly maximum water extent and depth maps revealing the inundation history in MDB

J. Teng [a], **C. Ticehurst** [a], **S. Marvanek** [a], **D. Penton** [a], **D, King** [a], **A. Freebairn** [a], **A. Sengupta** [a]

[a] *CSIRO Land & Water, Canberra, Australian Capital Territory*
Email: jin.teng@csiro.au

Abstract: Analysts use remote sensing to map flood extents for flood risk assessment, emergency response, water resource management, ecological evaluation, and many other applications. Remote-sensing-based flood extent mapping techniques are highly advanced (Ticehurst et al., 2021a) and data widely accessible (e.g. Digital Earth Australia's Water Observations from Space). However, flood water depth is not as easily obtained or readily available, especially when continuous observations are required over large spatial domains. This study improved the Floodwater Depth Estimation Tool (FwDET), first developed by Cohen et al. (2019), and used it to estimate flood water depth based on 33-year time series of two-monthly maximum multi-index surface water extents (Ticehurst et al., 2021b), DEM and gauged water depth for the Murray-Darling Basin (MDB). The result can be used to investigate physical and biological connectivity on the floodplain, to reveal the changes in inundation over time, and to develop metrics that are important for habitat, movement and dispersal of environmental assets.

The improved FwDET calculates water depth by first extracting boundary elevation of the flood extent from a DEM, interpolating water surface elevation using the boundary elevation, then subtracting the ground elevation from the interpolated surface elevation. The new version of the tool was written in Python and made suitable for parallel computing for a large domain at a high resolution. The boundary detection algorithm was also improved to account for areas without data and input data edges.

The resolution and accuracy of the DEM play a major role in the reliability of the estimated water depth. A method based on Gallant (2019) is used to merge and blend high resolution LiDAR DEM with the SRTM to provide continuous ground elevation so that the highest resolution/accuracy can be achieved wherever possible, and the abrupt changes at the border of two datasets attenuated within a 2km buffer.

The depth of the perennial channels and permanent water bodies was estimated using gauged water level from the Bureau of Meteorology's Water Data Online and added to the estimated water depth to take into consideration the areas that are under water when the DEM was collected.

The results are hosted on the Amazon Web Service (AWS) S3 bucket in the Cloud Optimised GeoTiff (COG) format, indexed in the Open Data Cube on the Earth Analytics Science and Innovation (EASI) platform and distributed using the OGC Web Map Service (WMS) for visualization on tools such as the Terria map.

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Keywords: *Flood inundation, water depth, remote sensing, Landsat, surface water*

Generating two-monthly surface water images for the Murray-Darling Basin

C.J. Ticehurst [a], **J. Teng** [a] **and A. Sengupta** [a]

[a] *CSIRO Land & Water, Canberra, Australian Capital Territory*
Email: catherine.ticehurst@csiro.au

Abstract: Mapping surface water extent is an important step in estimating water volume within a catchment, which is needed for managing flood events, as well as water supply for human consumption, agriculture, and the environment. Satellite-based remote sensing technologies provide an affordable means of capturing surface water extent with reasonable spatial and temporal coverage suited to the purpose of water monitoring. A new multi-index method (MIM) has been developed for mapping surface water across the Murray-Darling Basin (MDB) based on Landsat surface reflectance data available in Digital Earth Australia. More than thirty years of two-monthly images of surface water extent across the whole MDB have been produced using this method, along with Water Observations from Space (WOfS) to fill in any gaps associated with cloud cover due to the different cloud masks used (this combined product is referred to as MIM_WOfS_max). This product is currently being combined with a DEM to produce estimates of water depth across the basin and can be used with hydrology models for assessing connectivity between waterbodies. This product can also be used to assess long-term trends of surface water extent across the basin, as well as used for seasonal or bi-monthly analysis.

The methods used to produce the two-monthly WOfS and MIM products across the MDB are different and were based on utilizing the available cloud masks attached to the native products, and computational efficiency for generating the products. A comparison of the MIM and WOfS method shows that MIM identifies major perennial rivers and wetlands better than WOfS, as well as in some of the floodplain areas, while WOfS can identify more surface water in general areas where cloud cover still exists in the MIM product. A small mis-registration (up to 30 metres in some areas) between the MIM and WOfS products was also found – possibly due to the different native spatial projections of the datasets.

The MIM_WOfS_max product is used for identifying long-term and seasonal trends across the MDB. Over the 33-year time period (1988 to 2020) a reduction in surface water extent of 0.15% was found for the whole basin. The long-term trends of four sites were also investigated: two irrigated regions and two wetlands. They also showed a long-term reduction in surface water extent. The southern sites (one irrigated agriculture and one wetland) had regular annual flooding which gradually reduces in size through time, while the northern sites showed irregular flood patterns – with respect to the flood's timing and magnitude.

Details of the method used and challenges associated with producing the bi-monthly images of surface water across the MDB are provided in the paper, as well as further discussions on some of the long-term and seasonal trends that can be derived from this product for the entire MDB and selected regions within.

Keywords: *Surface water extent, remote sensing, Murray-Darling Basin*

Probabilistic tsunami inundation assessment from a near-field earthquake source

Kaya M. Wilson[a] and **Gareth Davies**[a]

[a] *Geoscience Australia, Symonston, Canberra, ACT 2609, Australia*
Email: kaya.wilson@ga.gov.au

Abstract: Tsunamis are a destructive and dangerous hazard for coastal communities. To prepare for future events, Probabilistic Tsunami Hazard Assessment (PTHA) can be used to estimate the frequency and severity of tsunamis. Large-scale PTHAs have been developed by modelling a suite of tsunami events to robustly represent all possible earthquake-generated tsunamis (Behrens *et al*., 2021). The 2018 Probabilistic Tsunami Hazard Assessment (PTHA18) is a global PTHA that serves as a database of offshore tsunami frequency and wave data (Davies & Griffin, 2018). In this presentation, we will demonstrate the efficient conversion of offshore PTHA18 data to onshore probabilistic inundation data (Figure 1) through the modelling of a stratified random sample of tsunami events. The town of Vanimo in Papua New Guinea (PNG) is used as a case study.

We consider the tsunami threat to the north coast of PNG from earthquakes generated in the New Guinea subduction zone. PNG does not currently have a comprehensive tsunami warning system. However, in the case of the New Guinea trench, ground shaking from a large earthquake may provide communities with some warning and, should this occur, PNG government advice is to evacuate to locations 800 m from the coastline (Kawata *et al*., 1999). Results suggest that this directive is a safe one and inundation further than 800 m inland is estimated to occur with a very low frequency. Evacuation to this distance from the coast may, however, not be achievable within the short period of time between a large earthquake on this trench and the resulting tsunami. Tsunami arrival times are estimated to be <10 min at an average frequency of roughly once in 300 years (Annual Exceedance Probability of 0.333). For Vanimo specifically, this guidance may be best followed in combination with evacuation to at least 5 m elevation. This allows for evacuation to the high elevation Vanimo peninsula (Figure 1) which is close to population centres on the isthmus, and is estimated to be inundated less frequently than other sites within 800 m of the coastline.

The offshore PTHA maximum water levels above Mean Sea Level (MSL) show a positive linear correlation with onshore maximum water levels. Linear regression data for every 10x10m cell in the model domain shows how the elevation features influence tsunami wave amplification. The linear regression coefficient at the coastline (0 m elevation) is between 1 and 1.6 with R^2 varying between 0.8 and 0.95. Shoaling is apparent in the nearshore and amplification is greater on the exposed, seaward side of the Vanimo peninsula than in more sheltered locations. Such variation makes a good case for applying comprehensive probabilistic inundation as opposed to simpler methods. Conclusions may be applicable to other locations with a near-field source.

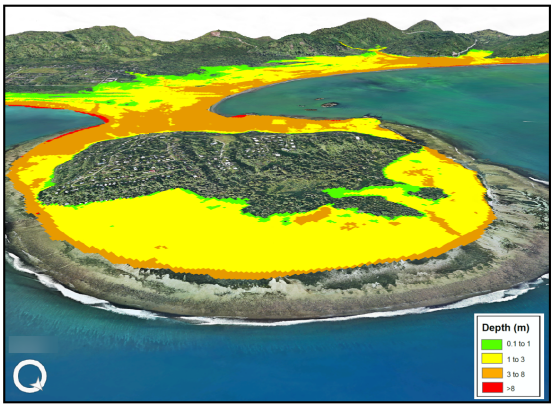

Figure 1. Probabilistic inundation depths for the town of Vanimo, PNG at an ARI of 2500 years (3D scene facing SSW).

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Keywords: *Tsunami, probabilistic inundation, probabilistic tsunami hazard assessment, coastal hazard*

EXTENDED ABSTRACT ONLY

Development of fast flood inundation emulator using deep learning with spatial reduction and reconstruction methods

Yuerong Zhou [a], **Wenyan Wu** [a], **Rory Nathan** [a] **and Quan J. Wang** [a]

[a] *Department of Infrastructure Engineering, Faculty of Engineering and Information Technology, University of Melbourne, Victoria 3010, Australia*
Email: yuerongz@student.unimelb.edu.au

Abstract: The ability to rapidly estimate flood inundation is of key advantage to many applications such as large-scale flood simulation, real-time ensemble flood forecasting, and uncertainty analysis for flood risk management. The computational burden of traditional 2D hydrodynamic models leads to prolonged run times and severely limits their applications. Flood inundation emulators which utilise 2D model results have gained attention in the recent years and have been found suitable for fast modelling of inundation. This work presents the development of a fast flood inundation emulator using deep learning (DL) models. A novel spatial reduction and reconstruction (SRR) method is also introduced as part of the emulator to simplify the development of DL models and to improve simulation efficiency. The inundation emulator translates streamflow discharge and water level boundary conditions into predictions of the extent and depth of flood inundation.

The SRR method is used to (1) decode the spatial correlation of inundation surfaces and find the representative locations across the modelling domain, and (2) reconstruct the entire flood water surface with the DL-modelled water levels at representative locations. The DL models are developed to handle multivariate timeseries inputs and to output water levels at representative locations with the Long Short- Term Memory (LSTM) architecture.

The emulator is developed to model flood inundation for a real-world case study in Queensland, Australia, with an area of 1153 km^2 and a model resolution of 20 m. The training data consists of 70 design flood events simulated using a TUFLOW 2D hydrodynamic model. The accuracy of the emulator is evaluated by comparing the maximum inundation extents and the temporal change of flood characteristics including water depth at each grid cell (see Figure 1), flood extent, and total inundation area. The emulator takes less than 2 seconds to simulate one flood inundation surface of over 2 million grid cells, which is over 42 times faster compared to the 2D hydrodynamic model.

The inundation emulator can be used for real-time forecasting as well as flood modelling applications where many model runs are required, such as for uncertainty analysis.

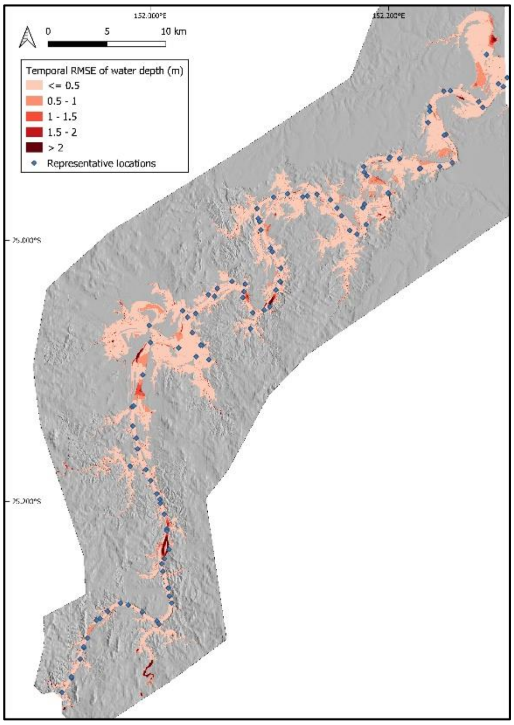

Figure 1. Temporal RMSE of modelled water depth compared to TUFLOW model results.

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Keywords: *Flood inundation modelling, deep learning, spatial reduction, LSTM*

High-resolution Quantile-Quantile scaled climate scenario projections for Australia

Raktima Dey[1], Vassili Kitsios[2,3], Marcus Thatcher[2], Craig Heady[2] and John Clarke[2]

[1]CSIRO Oceans and Atmosphere, Clunies Ross Street, Black Mountain, ACT 2601, Australia
[2]CSIRO Oceans and Atmosphere, 107-121 Station Street, Aspendale, Victoria 3195, Australia
[3]Laboratory for Turbulence Research in Aerospace and Combustion, Department of Mechanical and Aerospace Engineering Monash University, Clayton, Victoria 3800, Australia
Email: raktima.dey@csiro.au

Abstract: General circulation models (GCMs) provide climate data at a coarse spatial resolution in the order of ~100 km. These datasets are often not directly usable for applications that require bias-corrected fine scale information such as climate analyses for agriculture, electricity, and banking sectors. A novel quantile-quantile (QQ) scaling method is applied to observational dataset using climate change data generated by models contributing to the fifth coupled model intercomparison project (CMIP5). This approach effectively provides future projections of key climate variables at 0.05° (~5km) resolution. The method uses changes in climate variables between future and historical scenarios. Eight climate models were used to create the latest QQ-scaled dataset for three future emissions scenarios. These scenarios are referred to as representative concentration pathways (RCPs), with nominally 8.5 W/m^2, 4.5 W/m^2 and 2.6 W/m^2 of radiative forcing at 2100. These eight selected models are those recommended in the 2015 Climate Change in Australia technical report *(CSIRO & BoM, 2015)* as a nationally representative subset. The models were chosen based on a range of factors including the ability to capture the historical climate, representation of large-scale processes and teleconnections, adequate data availability for key climate parameters, independence of core models, and the ability to capture the range of projections of temperature, rainfall and windspeed.

The QQ scale method is applied on daily data for each month, extracted over a climatological historical and future period. One hundred and one quantiles (0,1,2,…100) were calculated at each grid point for both historical and future model simulations of a particular month. A change factor was then calculated between historical and future data for each quantile. The reverse quantile is calculated using the Australian Gridded Climate Data (AGCD) 1.0 observational data for a particular month over the period 1986-2005, i.e., a quantile value is assigned to each daily value. Next, the change factor for that particular quantile is applied to the observed daily data to obtain the projections data. For this dataset, we produced future projections for two 20-year periods, 2021-2040 and 2041-2060, taking the historical climate period as 1986-2005. The QQ method was applied to daily data for each month and thus conserves the seasonal variability in observational and model datasets. The method attempts to minimise model biases as change in quantile is used instead of mean change. Finally, the QQ scaled data are corrected so that the change in climatological monthly mean between observations and QQ-scaled data matches the GCM simulated change in monthly mean.

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Keywords: *Bias correction, regional projection, scaling, statistical downscaling, CMIP5*

A minimum-disruption approach to disaster analysis

Manfred Lenzen [a] and Mengyu Li [a]

[a] ISA, School of Physics, The University of Sydney, NSW 2006, Australia
Email: manfred.lenzen@sydney.edu.au

Abstract: There exists a number of disaster analysis streams that make use of economic input-output (IO) analysis in order to focus on socio-economic dimensions of disasters. In this work, we are particularly interested in using IO frameworks for investigating changes in consumption possibilities as a result of disaster-induced production shortfalls. There exist a number of shortcomings in existing approaches, amongst which are: the possibility of negative final demand, the inability to describe product substitution, and the inability to incorporate decision-makers' priorities. In this work, we propose an improved disaster analysis approach, characterised mainly by the ability to control for which parts of the economy decision-makers might want to shield from the disaster. More specifically we want to

a) be able to specify that a disaster shall affect some sectors of the economy less than others, and some not at all. For example, partial power blackouts should affect schools only temporarily, supermarkets and cool-store facilities even less, and hospitals not at all;
b) allow industries to substitute alternative inputs for reduced inputs. For example, industries may substitute unavailable inputs with imports of the identical product, or may use alternative technologies or materials.

Mathematically, we use a constrained optimisation approach with a minimum-disruption objective function $(x^{\text{pre}} - x^{\text{post}})^2$, as well as linear, non-linear and inequality constraints describing production shortfalls and fundamental economic balances. To model the socio-economic implication of this case study, we use a global data set comprising 61 regions with 26 sectors each constructed in a cloud-based collaborative research infrastructure, the Global MRIO Virtual Laboratory.

We demonstrate our new approach through an application to a case study: The consequences of Venezuela's drought and oil revenue plunge. In this case study, we simulate two concurrent trends between 2013 and 2016. First, crude oil production and refinery throughput halved in physical terms, accompanied by a fall of global crude oil prices from 100 to around 50 US$ per barrel, slashing Venezuela's export revenues (90% of which derive from crude oil) by three quarters (Fig. 1). Second, Venezuela's hydroelectricity production (representing roughly three quarters of installed capacity) fell from 18.9 to 13.9 mtoe, leading to a 9.4% decrease in electricity consumption (Fig. 1) and to rolling blackouts. The main reason for this decline was a shortage of reservoir stores in the Caroní River hydropower installations in Venezuela's Guayana Region, caused by ongoing drought conditions, peaking during the 2016 El Niño event.

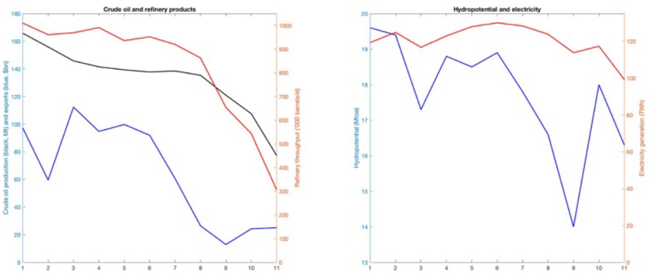

Figure 1. Trends in Venezuela's crude oil production and exports, refinery throughput, hydropotential and electricity generation.

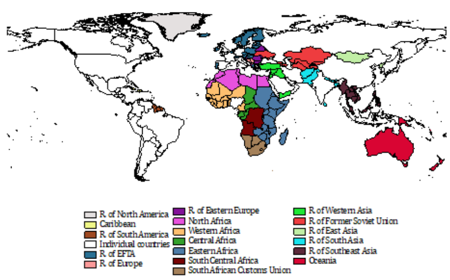

Figure 2. Regional classification used in this study.

Crude oil production in Venezuela is managed by the state-run energy company Petróleos de Venezuela SA (PDVSA) that had been struggling after the global oil price crash in 2014 that severely slashed the revenue for its crude oil exports. Problems at refineries arose largely as a result of component failures and the departure of key staff in PDVSA's trade and supply unit who were key to ensuring that production would generate revenues that would in turn provide the basis of payments for much-needed imports. This resulted in a shortage of basic necessities (petrol, power, food), and a deepening economic crisis under President Nicolás Maduro.

Keywords: *Socio-economic modelling of disasters, input-output analysis, drought, oil price plunge*

Climate and its impact on the Australian critical care services

E.K.W. Poon [a], **V. Kitsios** [b,c], **D. Pilcher** [d,e,f], **R. Bellomo** [f,g] **and J.S. Raman** [h,i]

[a] St Vincent's Hospital, University of Melbourne, VIC 3065, Australia, [b] CSIRO, Oceans & Atmosphere, VIC 3195, Australia, [c] Laboratory for Turbulence Research in Aerospace and Combustion, Department of Mechanical and Aerospace Engineering, Monash University, VIC 3800, Australia, [d] Department of Intensive Care, Alfred Hospital, VIC 3004, Australia, [e] The Australian and New Zealand Intensive Care Society (ANZICS) – Centre for Outcome and Resources Evaluation, VIC 3124, Australia, [f] The ANZICS – Research Centre, School of Public Health and Preventive Medicine, Monash University, VIC 3004, Australia, [g] Department of Critical Care, The University of Melbourne, VIC 3010, Australia, [h] Austin Hospital Clinical School, VIC 3084, Australia, [i] Department of Surgery, University of Melbourne, VIC 3065, Australia
Email: epoon@unimelb.edu.au

Abstract: Global warming and climate variability continues to disrupt our health, economies, and our lives. Extreme weather events and natural disasters pose a threat to humanity and our existence healthcare system. Correlative assessments between climate elements and critically ill patients admitted to intensive care units (ICUs) are urgently needed for better medical resource management and planning.

ICU admissions and the length of stay are key indices to illness severity and outcomes of critically ill patients. Surprisingly, despite increasingly recognised seasonal patterns in Australia's ICU admissions, it is uncommon for clinician scientists to have access to detailed climate analysis dataset and modelling. Hence, the full extent of climate change on Australia's healthcare demands remains poorly understood and unexplored.

We have recently gained access to two large, detailed datasets, 1) The Australian and New Zealand Intensive Care Society (ANZICS) Adult Patient Database, and 2) CSIRO Climate retrospective Analysis and Forecast Ensemble (CAFE60), as an urgent response to identify the impact of climate on our critical care services.

The ANZICS Adult Patient Database (https://www.anzics.com.au/annual-reports/) is a clinical quality registry run by the ANZICS Centre for Outcome and Resource Evaluation for quality benchmarking purpose since 1995. This dataset presently collects deidentified patient data on approximately 95% of ICU admissions within Australia. It provides a wide range of information, such as, basic diagnostic, illness severity and outcomes including length of stay in ICU, etc., in support of research understanding governance arrangements.

The CAFE60 is a probabilistic reconstruction of the global climate since 1960 (O'Kane et al., 2021a; 2021b). The CAFE60 contains the largest ensemble of Earths as compared to any other like dataset currently available. It comprises 96 simultaneous numerical simulations of the Earth, with each simulation started from slightly different setting to represent our best approximation of historical climate state and uncertainty.

We observed faster growth in ICU admissions than the Australian population in the last decade, and statistically significant relationships between multi-year changes in ICU admissions and multi-year natural climate variability. The cold and wet La Niña periods were associated with longer ICU length of stay. The hot and dry El Niño periods were associated with shorter length of stay. This study underpins an all-important strategy in the development of an ICU loading model based on accurate climate forecast, providing evidence-based recommendations to relevant authorities on optimising ICUs capacity at a local, national, and global level.

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Keywords: *Climate change, El Niño Southern Oscillation, intensive care units, critical care services*

The impacts of the El Niño–Southern Oscillation on global food security: An implied volatility approach

H. Yahyaei [a], **V. Kitsios** [b] **and L. De Mello** [a]

[a] *Department of Applied Finance, Macquarie Business School, Macquarie University, NSW, 2190, Australia,*
[b] *CSIRO Oceans and Atmosphere, Aspendale, Victoria, 3195, Australia*
Email: hamid.yahyaei@mq.edu.au

Abstract: This study investigates the implications of El Niño–Southern Oscillations (ENSO) on global food security. Employing a novel methodology that exploits the informational content embedded within options contracts, we reveal that our innovative measure of an ensemble-based ENSO inflicts a robust and consistent influence on the implied volatilities of core food inputs.

We show that the magnitude of risk spillovers across four key food products (Wheat, Maize, Rice, & Soybean) are significantly affected by innovations in our ENSO measure, suggesting climate variability plays a dominant role in inducing uncertainty. Furthermore, a series of bi-variate impulse response functions exhibit the dynamic path of implied volatilities following an unexpected ENSO shock, revealing an amplified degree of vulnerability of the food products to climate variability over the longer-term.

We suggest that our approach and findings can guide policymakers in better addressing food security concerns by examining the inferences on uncertainty derived from financial instruments. Specifically, ex-ante measures of future uncertainty embedded within options contracts provides a more informative window into the expectations of market participants, enabling better hedging strategy formation. In all, our work reinforces the importance of studying the dynamic between variations in the climate and food security, encouraging further research in this area.

Keywords: *ENSO, food security, implied volatility, options*

Modelling the third COVID-19 pandemic wave in Australia

Sheryl L. Chang [a], **Oliver M. Cliff** [a,b], **Cameron Zachreson** [a,c] **and Mikhail Prokopenko**[a,d]

[a] *Centre for Complex Systems, Faculty of Engineering, The University of Sydney, NSW, 2006, Australia*
[b] *School of Physics, Faculty of Science, The University of Sydney, NSW, 2006, Australia*
[c] *School of Computing and Information Systems, The University of Melbourne, VIC, 3052, Australia*
[d] *Sydney Institute for Infectious Diseases, The University of Sydney, NSW 2145, Australia*
Email: sheryl.chang@sydney.edu.au

Abstract: The third pandemic wave in Australia started in mid-June 2021. The ongoing epidemic is of great concern because of the high infectivity of the Delta variant and a delayed vaccination campaign in Australia. We used a re-calibrated agent-based model that includes about 24 million software agents representing the Australian population (Chang et al., 2020; Zachreson et al., 2021; Chang et al., 2021), with the aim to quantify effects of non-pharmaceutical interventions (case isolation, home quarantine, school closures, and social distancing, comprising several stay-at-home restrictions) and pharmaceutical interventions (progressive vaccination rollout). The model accounts for a shortened incubation period, an increased fraction of symptomatic cases in children, and the basic reproduction number (R_0) of 6.2.

The study estimated the timing and the extent of incidence stabilisation in mid-October. Our findings show that the Delta variant amplifies any lack of social distancing (SD) significantly compared to the ancestral strain and the current social distancing level (estimated as 50% of population adhering to social distancing rules, SD=0.5) is inadequate to contain the ongoing pandemic.

We also considered a possible "worst-case" scenario under which all stay-at-home restrictions are fully removed at the end of October. This scenario is not a forecast of the dynamics which are likely to develop once the restrictions are eased with the adult vaccination rate reaching 70% nationwide. Instead, it is a counter-factual scenario showing a potential surge of post-lockdown infections in the absence of any remaining restrictions. This "worst-case" scenario is shown in Figure 1, highlighting an extreme possibility that new cases may peak at tens of thousands per day. We argue that with increasing vaccinations there is a path out, but as a society we can choose to land softly after reopening, maintaining targeted SD and ensuring a better preparedness of the healthcare system. We also suggest that eligible children must be included in a rapid vaccination rollout.

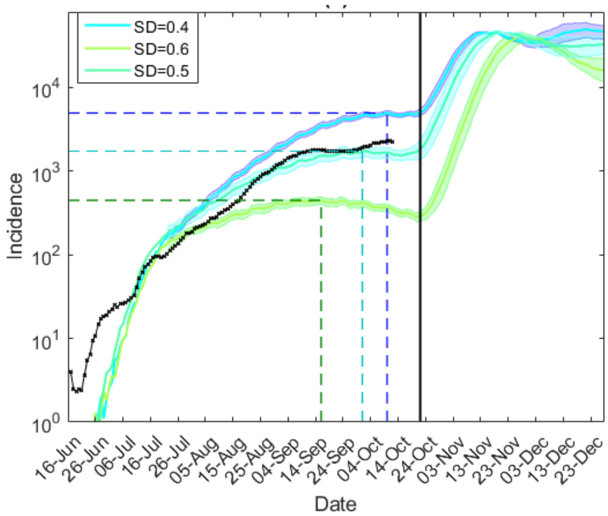

Figure 1. Incidence (log scale). The vertical black line separates nowcasting modelling up to mid-October and a counter-factual "worst-case" scenario until the end of the year. Actual incidence is shown with black crosses.

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Keywords: *COVID-19 modelling, agent-based modelling, social distancing, vaccination*

Discrete event simulation of intensive care in NSW, Australia during the 2020 / 2021 COVID-19 pandemic

Danielle Currie and Cindy Peng

Decision Analytics, The Sax Institute, Sydney, NSW, 2037, Australia
Email: Danielle.currie@saxinsitute.org.au

Abstract: COVID-19 has placed additional pressure on the finite resources in the health system, pushing many near the breaking point. To maintain health outcomes for the population, the allocation and management of physical and human resources within health systems is crucial. While models that predict community infections of COVID-19 and its related demand on health system are numerous, models that examine the 'how' of the health system response to COVID-19 have not received the same level of attention. The need for such models is particularly relevant in the context of Intensive Care Units (ICUs) where COVID-19 has placed significant pressure on units that are, by their nature, more challenging to flex than others (e.g. a workforce of highly-specialised and trained staff, medically fragile patients, high resource needs per patient, highly varied patient length-of-stay, etc.).

To help fill this gap, as part of the New South Wales (NSW) state response to COVID-19 we worked closely with NSW Health department to rapidly develop a discrete event simulation model to achieve the following objectives: 1) to improve the understanding of the overall capacity of intensive care units (ICU) in NSW; 2) to predict non-COVID elastic and inelastic demand on ICUs; and 3) to test different demand scenarios.

The model development process combined 'soft' knowledge and 'hard' data. A rapid and intensive participatory modelling process with clinical leaders and policy decision makers was undertaken to ensure the model development process considered the perspectives of those who will use and who will be impacted by the findings from the model. Input data were drawn from a range of existing administrative data sources, which had overlap as well as discrepancies. The stakeholders, therefore, not only informed the logic and structure of the mode, but also participated in informal survey and Delphi processes to validate the data inputs. The model was iteratively refined weekly with stakeholders' feedback and updated data was incorporated to improve its validity.

The resulting model simulates patient flows in eleven different ICUs across the metro Sydney area under various COVID-19 and health system management scenarios. The model simulates the various channels by which patients are referred to the ICU such as presenting to emergency department, undergoing elective or emergency surgeries, or being transferred from inpatient wards, as well as the various channels through which people exit the ICU. As admissions related to elective surgery are generally the main source of elastic demand on ICUs, a detailed structure related to demand from elective and emergency surgeries was also included in the model. To quantify the changes in physical and human resources required under different COVID-19 scenarios, the model was designed to capture staffing availability and need, as well as to predict levels of consumption of key items of personal protective equipment. Several large administrative datasets were used to assign characteristics and transition probabilities to patients flowing through the model, as well as capture the case-mix variation between hospitals. These generated estimates of elastic and inelastic demands on ICU resources, including physical beds and staffing. The model was run stochastically to generate 10^{th} – 90^{th} percentile of outcomes.

The value of the model is two-fold. The transparent and consultative process itself improved the understandings of the current system, such as, different definitions and measurement of 'capacity', and discrepancy in data sources. The outputs of the model were reported to various stakeholders involved in planning for COVID response in NSW Health and helped inform decisions, for example, cancelling of elective surgeries, and patient and resources allocations. As we move into a phase of learning to live with COVID, hospitals may face a new level and mix of demand, not to mention a requirement to quickly surge up in time of future outbreaks, and we are planning to further expand the model to support these decisions.

Keywords: *COVID-19, intensive care, health systems, decision making, discrete event simulation*

Model-based machine learning to explore the nexus between COVID-19 and environmental factors in the United States

[a]Munir, T., [b]Hudson, I. L., [c]Cheema, S. A. [a]Muhammad, R., [a]Shafqat, M., and [a]Kifayat, T.

[a] Department of Statistics, Quaid-i-Azam University Islamabad, Pakistan. [b] Mathematical Sciences, College of STEM, School of Science, Royal Melbourne Institute of Technology, Melbourne, Australia. [c] Department of Applied Sciences, National Textile University Faisalabad, Pakistan.
Email: *irene.hudson@rmit.edu.au*

Abstract: The aim of this study is to demonstrate the applicability of machine learning methods to understand the transmission of the viral flow of COVID-19 with respect to various environmental factors. Daily update data of **new** COVID-19 related reported cases from six states of the United State (US), dated from 1st March 2020 to 30th November 2020, across 6 US states - *New York*, *New Jersey*, *Illinois*, *Massachusetts*, *Georgia* and *Michigan* are examined. The daily COVID-19 update data are assembled from the US health department and Weather Underground Company (WUC) official websites. A diverse set of environmental factors, including temperature, humidity, dew point, wind speed, atmospheric pressure and precipitation are used to express possible environmental determinants. Asymmetric distributions of daily reported new cases of COVID-19 with respect to all states is evident. The average numbers of new reported cases of COVID-19 patients remains highest in *Illinois*. Whereas maximum numbers of affected cases in a single day were reported in *Georgia*. The lowest of the average new cases is found in *Massachusetts* state.

We test six most used model-based machine learning methods, namely, linear discriminant analysis (LDA), classification and regression trees (CART), k-nearest neighbours (KNN), support vector machines (SVM), random forest (RF) and the naïve bayes (NB) method. The comparative performance of these ML schemes is expressed using statistics, such as kappa, balanced accuracy, detection rate, information preservation rate, accuracy, sensitivity, and specificity. Moreover, predictive orderings of the environmental factors, for each state with respect to the most promising ML method, are also reported to highlight the hierarchical significance of climatic determinants. The performance orderings of the ML approaches vary across states with the RF model the most promising in exploring the underlying nexus of between the environment covariates and case numbers across all states, the ML hierarchies are: ***New York:*** $P_{RF} > P_{KNN} = P_{CART} = P_{SVM} > P_{LDA} > P_{NB}$, ***New Jersey*** : $P_{RF} > P_{LDA} = P_{SVM} > P_{NB} = P_{CART} > P_{KNN}$, ***Illinois:*** $P_{RF} > P_{KNN} = P_{SVM} > P_{NB} = P_{CART} > P_{LDA}$, ***Massachusetts:*** $P_{RF} > P_{SVM} > P_{CART} > P_{KNN} > P_{NB} > P_{LDA}$, ***Georgia:*** $P_{RF} > P_{SVM} > P_{CART} > P_{KNN} = P_{NB} > P_{LDA}$ and ***Michigan:*** $P_{RF} > P_{KNN} > P_{SVM} > P_{CART} = P_{NB} > P_{LDA}$. Noting that procedures such as CART, NB and LDA show questionable performance where *Michigan* state is concerned.

Across the states, average temperature emerges as the most important candidate in explaining the underlying nexus between environment and COVID-19 numbers, consistent with Shahzad et al. (2020). However, we have found that other climate variables such as dewpoint, is a close second in *Georgia* and *Michigan* states, and humidity and wind speed play a similarly important role to dewpoint in *Illinois* and *Michigan*. Note *Georgia* and *Michigan* states have highest average temperature and dew point, and both states record low average wind speed. *Michigan* has a reported high black community, as does Georgia. For *Illinois*, temperature is dominant, but followed by dew point, and then closely by **both** humidity and wind speed, with *Illinois* having lowest average wind speed and low temperature. There is less evidence for an association between air pressure and precipitation and COVID-19 cases in all states. Finally, based on the outcomes of this research, we believe that a more rigorous study targeting other variables, such as population density, mobility, air quality, nature of travel bans, race, and the degree of health interventions, is required. Furthermore, understanding the potential for seasonality and the association with weather is particularly relevant for further work given the longer time series of COVID-19 information now available in 2021, as is modelling new cases, transmission, along with deaths, reproduction number and severity levels of COVID-19. Given the skewed nature of the distribution of number of reported cases in each state, future work could likewise employ the quintile regression approach.

Keywords: *COVID-19, environmental covariates, machine learning model*

An agent-based model of the spread of COVID-19 in West Java, Indonesia

N. Ravindranath[a], V. Lemiale[a] and R. Idzalika[b]

[a] CSIRO Data61, Clayton, Australia, [b] Pulse Lab, Jakarta, Indonesia
Email: vincent.lemiale@csiro.au

Abstract: Computational models have played a key role in the management of the COVID-19 pandemic around the world (McBryde et al., 2020). However, the urgency of the health crisis forced the rapid development of such models under conditions of considerable uncertainty (Edeling et al., 2021). For example, from an epidemiological perspective, very little was known about the virus early in the pandemic. Moreover, reliable datasets were often not readily available and/or sufficiently fine-grained to accurately capture the specifics of a mobile population and simplifying assumptions had to be made. This work reports on a case study of a model developed as part of an Australian-Indonesian partnership for the management of COVID-19 in Indonesia and illustrates our experience in dealing with some of these challenges.

In this work, the spread of COVID-19 in Bekasi city, West Java, Indonesia was simulated using an agent-based model built using an in-house software called PiXIE (https://research.csiro.au/pixie/). In the model agents were assigned weekly activity plans depending on whether they were a full-time worker, part-time worker, student or not in the workforce. In principle there were no limitations on the type of activities an agent could undertake, although in practice the limited availability and level of refinement of mobility data led to simplifying assumptions. Agents then interacted through their daily activities and if they visited the same place at the same time, an infected agent could potentially spread the virus to other agents not yet exposed to the virus. The SEIR (Susceptible, Exposed, Infectious, Recovered) epidemiological was implemented in PiXIE, a model extensively used in COVID-19 modelling studies, see for example (Silva et al., 2020). The model allowed for the estimation of the infection rate over a specified period and the simulation of the effect of various possible measures to contain the spread, including health measures, as well as general restrictions imposed on the movements of individuals.

A two-step process was adopted for our modelling, whereby the model was first calibrated as best as possible against historical data extracted from the August 2020 to February 2021 period, prior to being used as a predictive tool to simulate possible scenarios for the May to July 2021 period. The one-to-one comparison with real-world data proved challenging, however. The model tended to overestimate the number of infected cases compared to reported data. This was in part attributed to the fact that many cases were not detected, owing to the large number of asymptomatic individuals in a young Indonesian population, combined with testing rates that were under the recommended World Health Organization threshold for some time in Indonesia. Our predictive simulations qualitatively estimated the potential impact of reopening schools either partially or fully in the May-July 2021 period. Our simulations predicted that a sharp rise of infections was to be expected, irrespective of the scenario considered, thus demonstrating that other factors such as workplace and household transmissions were predominant in driving the rise of infections in the population.

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Keywords: *COVID-19, modelling, agent-based model, disease spread*

Employment vulnerability of tourism workers during the COVID-19 pandemic – A global analysis

Ya-Yen Sun[a] **and Mengyu Li**[b]

[a] *UQ Business School, The University of Queensland, Brisbane Qld 4072 Australia,* [b] *School of Physics, The University of Sydney, Sydney, Australia*
Email: y.sun@business.uq.edu.au

Abstract: Tourism is among the most-affected sectors across the globe due to all counter-disease measures during the COVID-19 pandemic. The COVID-related tourism economic loss is estimated to be eight times larger than those experienced during the 2008 global financial crisis. Yet, no detailed tourism employment vulnerability is available in this unprecedented tourism crisis. The aim of this study is to provide a comprehensive job risk assessment for the tourism-related employment during the COVID-19 pandemic at the global scale. Our study first identifies how reduced international tourism consumption affects employment by gender, age and income status in 135 countries and regions. Secondly, we analyze the tourism job losses patterns against country's unemployment rate and the extent of the COVID financial and social support to proxy the risk of reducing incomes and social welfare. Based on these two steps, the most marginalized and vulnerable communities that have been heavily impacted by the tourism decline during the pandemic are identified.

Based on the global tourism receipts reduction, the extent of sales reduction was estimated for four tourism related sectors: transport, lodging and restaurant, retailing and recreational service sectors for 132 countries. Employment is assumed to reduce in a direct ratio as the sales reduction, which is then maped to the demongraphic profile of the employees by gender, age and income level.

The result indicates that total inbound tourism loss across 132 countries was US$ 1.58 trillion in 2020, corresponding to 1.38% the global production losses. This placed 26.0 million (full time equilibrium) direct jobs at risk across the retailing & wholesales trade (9.5 million FTE), accommodation and restaurants (8.8 million FTE), transport (4.5 million FTE), and arts, entertainment and recreation (1.1 million FTE). Holding the international travel to the ground places a higher proportion of female workers (9.6%) unemployed, in comparison to male workers (8.9%). Job reduction is also expected to reach over 10.1% for youth while their counterpart cohorts, young adults (age 25~30) and adults (age 30+), experienced 9.6% and 9.3% job losses, respectively. Globally, tourism workers are found to be paid 5% lower than the national average with a significant gender pay inequality. Monthly salary of tourism female workers is 23% lower than their male counter parts, and they also earned 11% less than other female employees in the non-tourism sectors.

The significant employment losses on women, youth, and low-income workers are observed for both developing and developed countries. However, a bipolar pattern is observed regarding financial burdens on workers. Several developing countries that experienced significant tourism job loss risks are also those that face a very high unemployment rate with minimum COVID-related financial and social supports. The disadvantaged tourism workers and countries include Ethiopia (youth, low pay), Vanuatu (youth, low pay), Guyana (female), Namibia (female, low pay), and Cameroon (low pay). In contrast, developed destinations, although also facing significant tourism job losses, are provided with strong economic and social subsidiary supports, such as Netherland (youth), Demark (youth), Austria (low pay), and Slovakia (female). Workers in this context can expect smaller financial vulnerability. Overall, the collapse of international travel in 2020 is likely to exacerbate the income and social inequality within and between countries due to the asymmetrical job losses and the unequal policy support environment globally.

Keywords: *Employment vulnerability, COVID-19, tourism workers*

Modelling COVID-19 using a novel SEIR-e model

T. A. Tambyah [a] **M. J. Testolin** [a] **and A. M. Hill** [a]

[a] *Modelling and Physical Sciences, Land Division, Defence Science Technology Group, Melbourne, Australia*
Email: tamara.tambyah@dst.defence.gov.au

Abstract: In 2019 a new coronavirus, SARS-CoV-2, was found to cause the respiratory illness commonly known as COVID-19. Originating in China, COVID-19 has resulted in a global pandemic and over 4.5 million deaths. While studies into the effect of infection prevention and control measures on the transmission of SARS-CoV-2 continue to evolve, available evidence suggests that SARS-CoV-2 is mainly spread through close contact with infected individuals in indoor settings, via inhalation of airborne respiratory droplets or fomites (World Health Organisation 2020).

Compartment models, such as SEIR models, are often used to model disease transmission resulting from interaction between susceptible and infected individuals (Bentout et al. 2020). However, there are limited instances considering how interaction with the environment, such as contact with contaminated surfaces, mediates the spread of disease. In this study, we develop a physics–based compartment model of an indoor environment with analytic solutions, referred to as the *environment model*, to investigate how inhalation and fomite transmission contribute to health effects, such as infection (Figure 1). We parametrise the model for SARS-CoV-2 to study the transmission of COVID-19 in indoor settings. To further study disease transmission due to interaction between people and pathogens, we develop a novel *SEIR–environment model* (SEIR-e) by coupling the environment model with a standard SEIR model (Figure 1). We derive an expression for the basic reproduction number which considers both people–people and people–pathogen interaction.

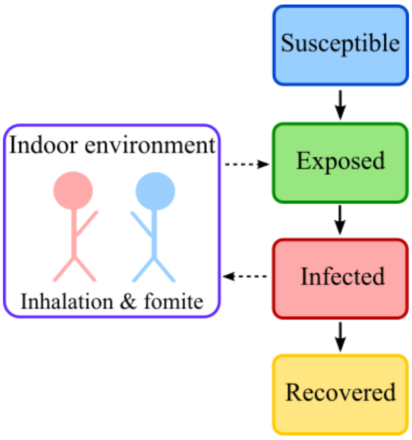

Figure 1. SEIR-e model with people–people and people–pathogen interaction

Due to the immediate threat of COVID-19 outbreaks, many studies use standard SEIR models and real–time case data to investigate disease progression, and to estimate the incubation and infectious periods for SARS-CoV-2 (Bentout et al. 2020). Such studies also estimate the rate at which susceptible and infected individuals come into direct contact, traditionally denoted as β. In 2020, the worst COVID-19 outbreak due to community transmission in Australia occurred in Victoria. Thus, we apply the SEIR-e model to corresponding case data, and use Bayesian techniques to estimate the incubation and infectious periods of SARS-CoV-2. We find these estimates align with reported values (Bentout et al. 2020). In addition, we infer parameters which reflect the rate of transmission due to people–people and people–pathogen interaction. As expected, these parameters differ from reported values of β as we consider inhalation and fomite transmission which is not explicitly included in standard SEIR models. While the applicability of the model developed in this study is demonstrated using SARS-CoV-2, the model is relevant to contexts involving other types of contaminates such as chemical, biological and radiological materials.

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Keywords: *Infectious diseases, compartment models, basic reproduction number, COVID-19 dynamics*

Health disparities of a vulnerable population burdened by air pollution

Sejong Bae PhD[a,b], Young-il Kim PhD[a,b], Rekha Ramachandran[a,b], Crystal T. Stephens CRNP[c], Monica Baskin, PhD[a,b] and Veena B. Antony MD[c]

[a]*School of Medicine, Department of Medicine, Division of Preventive Medicine, University of Alabama at Birmingham*
[b]*School of Medicine, O'Neal Comprehensive Cancer Center, University of Alabama at Birmingham*
[c]*School of Medicine, Department of Medicine, Division of Pulmonary, Allergy, & Critical Care, University of Alabama at Birmingham*
Email: bsejong@uab.edu

Abstract: Coal-fired power plants deposit heavy metals into the air, soil, and water; consequently, individuals residing in close proximity to these plants are increasingly stricken with lung diseases. The prevalence of chronic lung diseases, such as chronic obstructive pulmonary disease (COPD), asthma in children, and lower respiratory tract infections (LRTI), is significantly higher in the affected area compared to the neighbouring control area, irrespective of smoking, socioeconomic status, or demographics.

We conducted a retrospective analysis using data collected for patients visiting The University of Alabama at Birmingham (UAB) Health System. The data was obtained from the Enterprise Data Warehouse (UAB i2b2). We retrospectively evaluated healthcare utilization and classification of disease (defined by ICD-9 codes) of patients residing in zip codes: 35207 (affected), 35214 (control), and 35217 (affected).

The analysis results may provide evidence that can be used for risk mitigation strategies or outreach education campaign for those who live in the affected area.

Keywords: *Air pollution, coal factory, mitigation strategy*

Batch effect adjustment: Cancer vaccine clinical trial

Sejong Bae Ph.D. [a,b]**, Zhixin Wang, M.S.**[a,b,c] **, Chenguang Wang, M.A. Ph.D.**[d]**,**
Richard B.S. Roden Ph.D.[e] **and Warner Huh, M.D.**[f]

[a,b]*Division of Preventive Medicine, Department of Medicine, School of Medicine, University of Alabama at Birmingham, Birmingham, AL*
[b]*Comprehensive Cancer Center, University of Alabama at Birmingham, Birmingham, AL*
[c]*Department of Biostatistics, University of Alabama at Birmingham, Birmingham, AL*
[d]*Division of Biostatistics and Bioinformatics, Sidney Kimmel Comprehensive Cancer Center, The Johns Hopkins University, Baltimore, MD*
[e]*Department of Pathology, Sidney Kimmel Comprehensive Cancer Center, The Johns Hopkins University, Baltimore, MD*
[f]*Department of Obstetrics and Gynecology, School of Medicine, University of Alabama at Birmingham, Birmingham, AL*

Abstract: In cancer vaccine clinical studies, immune responses are commonly used as the primary endpoint for assessing vaccine efficacy. Simon's two-stage design is a popular clinical trial design in Phase II cancer studies. Nonetheless, it is not straightforward to apply it when performing immune assays in batches as outcomes from multiple patients may be correlated with each other in the presence of batch effects. This violates the independence assumption of Simon's two-stage design and correspondingly, may affect the clinical study in an unexpected way.

We numerically explored the impact of batch effects on Simon's two-stage design, proposed a batch-effect adjusted Simon's two-stage design, and demonstrated the proposed design by both a simulation study and a therapeutic human papillomavirus vaccine trial example.

When batch effects are neglected, trials have inflated type I error rates and deflated power. This negative impact worsens as the batch size increases. Adjusted Simon’s two-stage design controls both the type I and II errors well, suggesting itself as a promising solution for dealing with batch effects in Phase II cancer vaccine clinical studies.

Keywords: *Batch effect, cancer, vaccine, clinical trial*

Using participatory methods to develop place-based models for youth mental health systems

Louise Freebairn [a,b], Jo-An Occhipinti [a,b], Yun Ju C Song[a] , Sam Huntley[a] , Kenny Lawson[a], Grace Yeeun Lee[a], Nicholas Ho[a], Simon Chiu[a], Adam Skinner[a], Samuel Hockey[a] and Ian B. Hickie[a]

[a]*Brain and Mind Centre, Faculty of Medicine and Health, University of Sydney*
[a] *Computer Simulation & Advanced Research Technologies (CSART), Sydney, Australia*
Email: louise.freebairn@sydney.edu.au

Abstract: Mental ill-health remains a significant and intractable issue impacting on young people globally. The drivers for youth mental ill-health span multiple service sectors including social services, education, employment, housing and health. Advanced decision support methods, at multiple levels of scale, are needed to better understand the complex and dynamic interactions between the social determinants of mental ill-health and the service needs for communities. The *Right care, first time, where you live* program of research will implement system modelling for youth mental health in eight diverse communities across Australia to better understand local challenges and inform program and policy decision making (Occhipinti et. al. in press). In collaboration with a lead agency in each community, key stakeholders will be identified and invited to engage in a series of interactive participatory workshops to elucidate the local drivers of mental ill-health, map the service system and explore the potential impact of interventions as prioritized through the process. This presentation will outline the modelling process that will be implemented at two sites per year from 2022 to 2025 and will involve engaging a wide range of participants including young people with lived experience of mental ill-health, professionals from health and other sectors such as education, members of the Aboriginal and Torres Strait Islander community and community leaders from local groups with an interest or stake in the youth mental health system. The program will engage stakeholders prior to, during and after the participatory modelling process to build local capacity in the use of system models and maximize the potential benefits of the research program for the communities involved.

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Keywords: *Participatory modelling, youth mental health*

Closing the gender gap and improving Australia's mental health in the COVID-19 era

Nicholas Ho[a], Adam Skinner[a], Louise Freebairn[a,b], Jo-An Occhipinti[a,b] and Ian B. Hickie[a]

[a] *Brain and Mind Centre, Faculty of Medicine and Health, University of Sydney*
[b] *Computer Simulation & Advanced Research Technologies (CSART), Sydney, Australia*
Email: nicholas.ho@sydney.edu.au

Abstract: Almost half of the Australian population will experience mental ill-health in their lifetime (Australian Bureau of Statistics, 2008) and the economic costs of this has been estimated to be $600 million *per day* (Productivity Commission, 2020). The difference in adverse mental health outcomes between genders have been reported. For example, suicide death rates are higher in males (Australian Bureau of Statistics, 2021). In contrast, intentional self-harm hospitalisation rates, mental-health related emergency-department presentation rates and psychological distress prevalence are higher in females (Australian Institute of Health and Welfare, 2021; Australian Bureau of Statistics, 2018). Furthermore, the COVID-19 recession has impacted females harder than males (Wood et al., 2021) and this is reflected in the larger increase in psychological distress prevalence and the longer recovery to the pre-pandemic levels in females (Australian Bureau of Statistics, 2021b).

This presents an opportunity to simulate and test economic and health sector policies which may mitigate the labour force and mental health impacts of the COVID-19 recession and close this widening gender gap. To this, we built an age and gender stratified system dynamics model that captures the complex relationships between population demographics, labour force participation, mental health service pathways and capacities, psychological distress rates and suicidal behaviours. The model was tested on its ability to reproduce historical data and then used to simulate a variety of plausible national policies that may reduce adverse mental health outcomes.

In this presentation, we will discuss the model in greater detail, the projected mental health trajectories of Australians in the COVID-19 era and the strategies which can help mitigate the "shadow pandemic" of mental ill-health.

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Keywords: *Mental health, system dynamics, decision analysis*

Modelling social and occupational outcomes for young people who attend early intervention mental health services

Frank Iorfino[a], Ante Prodan[bcd], Matthew Varidel[a], Kirill Glavatskiy[a], Rehez Ahlip[c] and Ian B. Hickie[a]

[a] *Brain and Mind Centre, Faculty of Medicine and Health, University of Sydney*
[a] *Translational Health Research Institute, Western Sydney University*
[c] *Computer Simulation & Advanced Research Technologies (CSART), Sydney, Australia*
[d] *School of Computer, Data and Mathematical Sciences, Western Sydney University*
Email: frank.iorfino@sydney.edu.au

Abstract: Over 75% of mental disorder emerge before the age of 25 and they are the leading cause of disability due to their impacts on overall health and productivity (Gore et al., 2011). The objective of this project is to explore clinical predictors of social and occupational outcomes for young people who attend early intervention mental health services. Recent work identified that two in three young people with emerging mental disorders did not experience meaningful improvement in social and occupational function during two years of early intervention care and that most (~49%) functional trajectories were also quite volatile (Iorfino et al., in press). Longer periods of untreated illness are associated with poorer outcomes (Ghio et al., 2014) and so identifying predictors of poor outcomes is important for providing effective early intervention. This presentation will outline the modelling process that will be implemented to elucidate underlying causal mechanisms and develop the predictive model. We will describe an Agent Based Model (ABM) with a population of agents representing young people of which each contains a network of symptoms and psychosocial factors (i.e. alcohol use or physical health) associated with mental illness and apply network theory methodologies to model psychopathology (Borsboom et al., 2021). This approach will allow us to expose associations between behavioural patterns and the relationship between symptoms and other psychosocial factors. Furthermore, we will describe psychometric network analysis techniques we will use to investigate structural characteristics of such networks and their associations to system dynamics of mental health of young people. Finally, we will describe variance reduction methods that we intend to use to increase accuracy of the predictor.

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Keywords: *Mental health, agent based modelling, decision support*

The role of embodied cognition in linguistic mental health analysis

D. Kernot [a], M. Van Hooff [bc], E. Lawrence-Wood [bd], L. Glenny [e], C. Snowden [e], K. Green [e] and C. Son [e]

[a] Defence Science and Technology Group, Edinburgh, SA, Australia, [b] Centre for Traumatic Stress Studies, University of Adelaide, Adelaide, SA, Australia, [c] Military and Emergency Services Health Australia, Glenside, SA, Australia, [d] Phoenix Australia Centre for Posttraumatic Mental Health, University of Melbourne, Melbourne, Victoria, Australia, [e] University of South Australia, Magill, SA, Australia.
Email: david.kernot@dst.defence.gov.au

Abstract: Drawing on the intersection between embodied cognition and the referential process, where the human body and its environment influence the way a person thinks and feels, we compared two linguistic analysis approaches to see if it was possible to classify self-reported mental health in female veterans from their writing using words affected by the emotional and modality-specific systems in the brain. Drawing on self-reported PTSD, Depression, and psychological distress properties in the Diagnostic and Statistical Manual of Mental Disorders (DSM-5) we used interview transcripts (n=40) and compared them to normal bloggers' posts (n=25) and discovered statistically significant differences in language use (total of 330,000 words). We used two linguistic approaches, the Linguistic Inquiry Word Count (LIWC) tool, and an embodied cognition approach (Richness, Personal Pronouns, Referential Activity Power, and Sensory (RPAS) algorithm) to statistically correlate findings. In this exploratory study, findings suggested that deployed female military personnel have a distinct pattern of speech which is more blunted (use fewer unique words but more repetition) than women in the community. This style of language is often seen in individuals with anxiety and depression. Deployment length (2-20 months, average = 8.5) directly correlated to increased blunted speech and was related to an increased feeling of emotional numbness and greater un-conscious reliance on memories when generating language. There were also language differences in the female military cohort who self-report more mental health symptoms. Those with self-reported mental health conditions (n=7) used words that focussed on the past and used fewer 'they' type words and isolated themselves to minimise stigma. This stigmatised language implied female military deployees with mental health symptoms felt isolated from their peers, through 'othering' and members of an outgroup. This study supports the idea that linguistic analysis using embodied cognition can discriminate between military females with self-reported mental health and those without and may be a valuable aid in highlighting post-traumatic stress in veterans.

Keywords: *Mental health, post-traumatic stress, embodied cognition, LIWC*

Prototyping, developing, and iterating a gamified survey to evaluate participatory systems modelling for youth mental health: Quality assurance pilot

G.Y. Lee [a], **I.B. Hickie** [a±], **J. Occhipinti** [a,b±], **Y.J.C. Song** [a], **S. Huntley** [a], **A. Skinner** [a], **K. Lawson** [a], **S.J. Hockey** [a] **and L. Freebairn** [a,b,c]

[a] *Brain and Mind Centre, The University of Sydney, Australia,* [b] *Computer Simulation & Advanced Research Technologies (CSART), Sydney, Australia,* [c] *Research School of Population Health, The Australian National University, Australian Capital Territory*

[±] *Equal contributions*

Email: grace.lee@sydney.edu.au

Abstract: Gamification is rapidly gaining popularity in research, including in participatory modelling programs. To facilitate stakeholder engagement and learning, gamification is utilised to communicate complex systems challenges at all stages of participatory modelling. However, this has excluded evaluation processes. We argue that evaluation of participatory modelling is important for refining and improving participatory processes and describe the potential for gamification to provide a more appealing platform for participants to engage in evaluation activities, eliciting richer data. This paper describes a quality assurance pilot to prototype, develop, and iterate online surveys – specifically its gamified activities – in the context of evaluating a national youth mental health participatory systems modelling program. Usability testing of the gamified surveys will be undertaken with diverse participants, which includes a rigorous process to reflect user feedback into functional improvements of the gamified activities. Potential benefits of gamification, such as participant empowerment and depth (of stakeholder learning, data, etc), are also explored. Though described in the context of an evaluation study for a national youth mental health participatory systems modelling program, this paper encourages researchers across disciplines to flexibly adapt and consider the benefits of gamification in participatory modelling including evaluation.

Keywords: *Participatory modelling, gamification, evaluation, online surveys, youth mental health*

Functional components used in agent-based models of mental illness progression and intervention

Ante Prodan[abcd], Frank Iorfino[b], Kirill Glavatskiy[b], Matthew Varidel[b], Rehez Ahlip[d] and Ian B. Hickie[b]

[a]*Translational Health Research Institute, Western Sydney University*
[b]*Brain and Mind Centre, Faculty of Medicine and Health, University of Sydney*
[c]*Computer Simulation & Advanced Research Technologies (CSART), Sydney, Australia*
[d]*School of Computer, Data and Mathematical Sciences, Western Sydney University*
Email: ante.prodan@westernsydney.edu.au

Abstract: As computational models are becoming more common in psychology and psychiatry, there is significant demand for reusable, well understood and tested components to be used in these models. In this presentation we will discuss the technical aspect of developing such components of varying complexity and expressiveness. We will provide examples based on Capability, Opportunity, Motivation, Behaviour (COM-B) model, logistic functions, law of diminishing marginal returns (economics), spring mass (system) based on Hooke's law, and combined procedure of network structure estimation and network description (Borsboom et al., 2021). We will examine and demonstrate the most important properties of such models when they are used as part of Agent Based Models developed in AnyLogic.

Firstly, we will demonstrate the use of the COM-B model as an overarching framework for agent-based models in the mental health domain. Secondly, we will examine the use of generalized logistic function (Richard's curve) as a limit for the change in measures such as Social and Occupational Functioning Assessment Scale for diagnoses such as neurodevelopmental disorders or brain injury which is then extended to a spring mass model that includes additional representation of rebounding effect of the discontinuation of an intervention. Thirdly, we will demonstrate an implementation of the law of diminishing marginal returns as the model of the effect of an intervention to promote positive mental health. Finally, we will show the use of network structures to create a representation of occurrence of major depression by using partial correlations between symptoms (Van Borkulo et al., 2013).

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Keywords: *Mental health, computational epidemiology, mental disorders*

Health service utilisation and environmental influences in the Australian Capital Territory

A. Raulli [a], **P. Adhikari** [a], **G. Draper** [a], **E. Chalker** [a], **W. Holroyd** [a], **L.K. Kreuger and L. Freebairn** [a,b]

[a] *ACT Health Directorate ACT,* [b] *University of Sydney, Sydney NSW,* [c] *Kreuger Consulting LLC*
Email: Alex.Raulli@act.gov.au

Abstract: In August 2019, the Australian Medical Association (AMA) declared climate change a health emergency (https://www.ama.com.au/media/climate-change-health-emergency) and called on governments to promote education and awareness of the health impacts of climate change, and the public health benefits of mitigation and adaption.

At present, the ACT Government has limited data to estimate the impact of climate change on local health services and future health needs, and very little capacity to model future scenarios and policy options. This includes for example, the impact of increasing heat stress and how this will impact future health service requirements and costs. By implication, the impact of actions taken to mitigate the influence of climate change or how these actions may affect the cost of health services also cannot currently be estimated. This limits the Government's ability to prioritise responses to these impacts and identify critical times and conditions where additional emergency services may be required.

System dynamics modelling methods will be utilised to examine the relationship between environmental influences such as extreme temperature and air quality events. The project will model the impact of such weather extremes on health service utilisation in the ACT, with the overall intention of developing a dynamic model to enable the prediction of short-term surges in health service utilisation and demand due to environmental factors.

The initial phase of the project will focus on excess heat and its impact on health service utilisation with a specific focus on emergency department presentations, hospital separations, ambulance call outs, walk in centre occasions of service and excess mortality. This methodology will be expanded for the second phase, to model cold weather-related health service utilisation and excess mortality.

The model's output will contribute to the body of evidence and will be of immediate use to health service planning needs and assist in the development of risk mitigation strategies for potential climate related impacts on health service utilisation and demand. The model will also inform and support the work of other government agencies, including those with responsibility for climate action. The work will develop "in-house" capacity among staff within the Health Directorate's Epidemiology Section, improve the quality and validity of information that underpins policy development and enable the development of future policy analysis tools.

Keywords: *Climate Change, health systems, system dynamic modelling*

Participatory modelling in socio-technical systems

Bryann Avendano [c]

[a] *Department of Civil and Natural Resources Engineering, University of Canterbury, Christchurch, 8140, New Zealand*
Email: bryann@pg.canterbury.ac.nz

Abstract: Infrastructure decision-making reveals tensions between improving social and technical assets. Policymakers, planners, engineers, and communities must combine their expertise to understand complexities during infrastructure decision-making. Participatory modelling (PM), or modelling with stakeholders, has proven to be a powerful approach for enhancing the understanding of complex systems. PM is for communities and engineering projects dealing with negotiations that involve multiple stakeholders, critical comprehension of trade-offs, cost-benefit analysis, and multiple-criteria analysis.

The use of participatory approaches to tackle complex adaptive systems (CAS) has benefited decision-making processes in environmental science and management research over the past 20 years. This work proposes that similar approaches can be applied to study other complex adaptive systems, such as Socio-Technical Systems relevant to resilience decision-making. The aim is to guide civil and natural systems engineers into the practice of PM, revisiting advances that environmental scientists and managers have been using and providing key references, examples, and practical guidelines.

Precedents highlight three lessons when applying PM on decision-making processes in infrastructure: 1) listen to stakeholders to understand the complexity of the systems, 2) collaborate to model/simulate with stakeholders, and 3) co-decide actions to govern transformations. PM has advantages: participants bring their mental models, and through collaboration and mathematical conceptions, a model is developed to support decision-making processes, working together to decide on a better policy, but PM is not a panacea. Past work shows that challenges remain. The paper outlines challenges and obstacles to progress for future advances using PM for civil engineering applications. Findings to advance:

- The increased use and development of PM in civil engineering will broaden and enrich future modelling methods.
- PM can be applied to a wide range of civil engineering and environmental systems applications, including transportation systems, energy transitions to renewable sources, and water allocation negotiations.
- PM repurposes consultation into an engagement with communities that can both anchor models on an agreed foundation, and use the model for community-supported action.

The incorporation of PM within civil engineering work will be more useful to society when civil engineers understand better the operation of PM. However, engineers need to take care not to practice outside the limits of their competence, recognising that designing and facilitating a PM process requires significant expertise.
PM appears to be of greater value in larger projects involving complex Socio-Technical Systems. The next revolution to understand complexities during decision-making in civil engineering will consider participants as co-policy makers who will govern and lead the change.

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Keywords: *Community engagement, complex adaptive systems, critical infrastructure, decision-making*

Gamification of Discussoo: an online AI-based forum for serious discussions

E. Bakhanova[a], **M. Anjum**[a], **A. Voinov**[a], **W.L. Raffe**[b] **and J. Garcia Marin**[b]

[a]*Centre on Persuasive Systems for Wise Adaptive Living, University of Technology Sydney, Sydney, New South Wales*
[b]*UTS Games Studio, University of Technology Sydney, Sydney, New South Wales*
Email: elena.bakhanova@uts.edu.au

Abstract: Participatory modeling (PM) organizes stakeholder engagement around the process of building models of the systems of interest. This method has several challenges associated with its implementation. Modeling workshops are usually restricted in time (between 2 and 5 hours) and these workshops can accommodate only a limited number of participants (normally up to 30 people). It would be challenging to conduct a constructive discussion by inviting many more stakeholders and it will be hard to get all of them to join a workshop at a particular time in one place. One of the possible solutions to overcome these limitations is to use online discussion forums.

Discussoo is a tool that provides a platform for stakeholders where they can share their opinions or ideas by submitting comments, while the recorded comments are immediately processed and information is extracted from available texts in an attempt to generate on the fly some versions of conceptual models, which can be instantly fed back into the discussion for stakeholder checking and validation.

While involving multiple stakeholders in an online discussion provides an opportunity for groups and organizations to improve the quality of their decisions, they inevitably face a new set of challenges with regards to engaging people and managing conversations. Overall, people are time poor and overloaded with information and it's difficult to sustain a high level of participation, especially if the topic of discussion is not a top priority for a particular group of stakeholders. The anticipated challenges can be the following: (1) Retention of stakeholders at the platform, (2) Too many comments that need to be read by the participants, (3) No feeling of community or social presence, and (4) Validating the concepts extracted by AI algorithms for improving the mind map.

In this research, we propose possible game design solutions to the engagement challenge for an existing online AI-based platform Discussoo. More particularly, we suggest using a chatbot for keeping the conversation going, badges, embedded game for validating the concepts and a set of notifications to sustain involvement in the discussion. We also reflect on the preliminary results from expert interviews and a pilot study.

Keywords: *Asynchronous discussion, game design, stakeholder engagement, participatory modeling*

Participatory modeling for Artificial Intelligence

Gnana K Bharathy

ARDC and University of Technology Sydney, Australia,
Email: gnana.bharathy@uts.edu.au

Abstract: For majority of artificial intelligence (AI) practitioners, modern AI development has been an affair driven by data. Inspired by such traditions as participatory modeling (Voinov et.al. 2018), systems/ design thinking as well as drawing a leaf from previous generation of AIs (expert systems), there are some initiatives in the AI community that attempt to put human at the centre of the AI through tools. These tools aim to put human in the loop, review, alter and adapt the findings or recommendations (albeit after the model construction), empower the end-users to with particular aim of minimizing ethical biases. Google Research's People + AI Research (PAIR) and ICML 2020 workshop (Kulynych et.al. 2020) are case in points. However, participation in model development as often espoused by participatory modeling (PM) communities is missing. Through two AI case studies, this paper aims to fill the gap, explicating key elements of the PM for AI (**PM4AI**) projects. **Cases**: The first case (**Case CP** for Chemical Process) involved developing AI models for a petro-chemical plant with the primary aim of providing early warning for process deviations. The second case involved the development of AI for an insurance company (**Case IN** for Insurance Nudging), with the objective of developing an AI system to detect a range of behaviours from failures to fraud in certain group of customers, and employ nudging to encourage the corrective behaviour. Case CP was carried out in the Middle East and IN was in Australia. The author, heading a team of data scientists (large in CP and small in IN), engaged with the stakeholders (mostly plant engineers in Case CP, and business professionals in Case IN) in the process of designing and developing the AIs. The conceptual models of the AIs were collaboratively derived from extensive discussion with the stakeholders (domain experts, end-users etc.) using domain specific language and knowledge. Similarly, data pre-processing and exploratory data analysis were carried in small steps, and were exposed to the stakeholders, who could suggest further steps based on their experience. In the first case, in order to facilitate stakeholder interaction in design and development, the models were developed in a visual tool, namely Dataiku, and at every step were exposed to the end-users. In the second case, the machine learning system itself did not employ any visual tools (but python, SQL and SAS) codes, visualization tool was extensively used, and an explanatory AI was also developed. The validation and testing results were not only exposed and discussed, but also explanatory models were created to explain the predictions of more complex models to the stakeholders. As the models got to the deployment, overall stakeholder participation was replaced by larger proportions of end-users. In both cases, one of the main challenges pertained to data. The (both plant and business) processes changed over time, and therefore, it is often hard to use the data over a long period, affecting both quality and quantity of data. Where data challenge were paramount, we employed human knowledge to supplement data. In both cases, there were inflated expectations of what an AI would provide. In addition, Case CP was compounded by the complexity of the plant, aggressive schedule and hierarchical manufacturing culture, less familiar to data science. The extended interactions and participation that made stakeholders co-developers, mitigated some of the challenges and enabled managing expectations. However, the direct engagement was limited to the stakeholder team and did not automatically extend to senior decision makers. **Take away**: The cases demonstrate that participation in AI model construction is possible, advantageous, and improves accessibility, equity as well as overall value. The traditional culprits for PM: (1) often have an emotionally appealing problem, (2) have room for democratic knowledge elicitation, and decision-making, (3) involve systems models such as agent-based models, systems dynamics, etc., where visual conceptual models are co-developed through the PM exercises. These opportunities are generally lacking in PM4AI. For PM4AI to be effective, purpose, democratization and engagement (e.g. via visualization or gamification) must be created by design. It is also important to identify participants who have the knowledge, time and the drive to participate, as well as tolerant for uncertainty, for PM4AI would be a drawn out process laden with uncertainty and boring discussions. For the outcome to be useful, PM4AI should be dovetailing into the organizational decision making process and appeal to the business need of higher stakeholder involvement.

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Keywords: *Artificial Intelligence (AI), Machine Learning (ML), Participatory Modeling (PM), PM4AI*

Participatory social systems modeling

Gnana Bharathy [a, b], Barry Silverman [c, d], Daniel Silverman [c, e], Nathan Weyer [c] and William Tam [c, d]

[a] ARDC, [b] UTS, [c] Edutainics, [d] UPenn, [e] CMU
Email: gnana.bharathy@uts.edu.au

Abstract: This abstract summarizes the participatory aspects of social system model development for countries in conflict. Over the past 20 years, we have built a framework, named StateSim, to model countries based on a multi-resolution agent based approach as an architecture to synthesize many best-of-breed models and best practice theories of human behavior modeling. This environment facilitates the codification of alternative theories of factional interaction and the evaluation of policy alternatives. The framework allows for a virtual recreation of the significant agents (leaders, followers, and agency ministers), factions, institutions, and resource constraints affecting a given country and its instabilities. StateSim is an environment that captures a globally recurring socio-cultural "game" that focuses upon inter-group competition for control of resources.The approach and results are discussed on various papers (Silverman et.al. 2021). However, the participatory aspects has only been covered in a cursory fashion as knowledge elicitation from stakeholders in describing model validation and evaluation. This paper focuses on the participatory model construction.

We attempt to build our models rich in causal factors that can be examined to see what leads to particular outcomes. We also try to base our models on best currently available scientific theories of social systems and the other types of systems involved. In order to develop the models in this framework, we synthesize domain knowledge from multiple subject matter experts in a range of domains, where there is a high level of fragmentation. In the cases described, we recruited suitable stakeholders based on their expertise and involvement in the topic. The experts began with filling in a long survey that elicits their mental models, judgement and parameter estimates in their respective domains, including state of the country, key actors and groups, their interactions as well as various institutional factors. Typically, these are information that are difficult to obtain through existing datasets. This information from expert stakeholders is supplemented by information from the datasets. Often the information from disparate sources would not agree, and an uncertainty tolerant differential diagnosis process is applied to resolve or accommodate any conflicting information. The some of the stakeholders also co-construct the models with the tool. In addition to external validation exercises, a holistic model evaluation process (described in Bharathy and Silverman, 2013) is often applied that assess the model construction methodology, the structure, processes and mechanisms. The level of validation is commensurate with the need of the model. In using the model, the framework allows for injection of courses of action to intervene in the simulation, creating another opportunity for participation.

Conclusion: To date, a number of countries or regions of the world have been modelled for studying instability. The models allow participants to see through the countries. A series of external validity studies were also employed to evaluate the models, where the models performed well. However, this process required modeller to work with the experts extensively, synthesize disparate pieces, and create the models. It is also very time consuming, taking weeks, if not months to develop a country model. These have been limiting the extent of participation. In the recent years, we have been upgrading the software, so that a participant in the domain would be able to create a preliminary model in a short span of an hour or two. Various agencies in United States, UK and to a lesser extent in Australia have participated in the model creation process over last 20 years.

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Keywords: *AI, social systems modeling, participatory modeling, agent based modeling*

Towards a competency framework for participatory modeling: Identifying core competencies

S. Elsawah [a], E. Bakhanova [b], R. Hämäläinen[c] and A. Voinov[b]

[a] *Capability Systems Centre, University of New South Wales Canberra, Australia,* [b] *PERSWADE Center, University of Technology Sydney, Australia,* [c] *Systems Analysis Laboratory, Aalto University, Finland*
Email: s.elsawah@unsw.edu.au

Abstract: Participatory modeling (PM) is a craft that is often learned by training 'on the job' and mastered through years of practice. There is little explicit knowledge available on identifying and documenting the skills needed to perform PM. In the modeling literature, existing attempts to identify relevant competencies have focused on the specific technical skills required for specific technical model development. The other skills required to organize and conduct the stakeholder process seem to be more vaguely and poorly defined in this context. The situation is complicated by PM being an essentially transdisciplinary craft. In PM, we need to understand both modelling and people engagement, with no single discipline or skill set to borrow ideas and recommendations from. In this paper, we aim to set the foundation for both the practice and capacity-building efforts for PM by identifying the relevant core competencies. Our inquiry into this topic starts with reviewing and compiling literature on competencies in problem-solving research areas related to PM (e.g., systems thinking, facilitated model building, operations research, and so forth). We augment our inquiry with results from a PM practitioners' survey to learn how they perceive the importance of different competencies and how the scope of these competencies may vary across the roles. As a result, we identified five core competencies essential for PM: systems thinking, modeling, group facilitation, project management and leadership, and, more recently, designing and running virtual workshops and events

Keywords: *Participatory modeling, competency, skills, education, training*

Solving constrained K-Markov decision processes

Jonathan Ferrer-Mestres [a] and **Iadine Chades** [a]

[a] *Conservation Decisions Team, Land and Water, CSIRO*
Email: jonathan.ferrermestres@csiro.au

Abstract: Markov Decision Processes (MDPs) are convenient mathematical models used to solve sequential decision-making problems when the state of the system is completely observable and actions have an uncertain outcome. In human operated systems such as conservation of biodiversity and environmental management, solutions that cannot be understood or explained to human experts are unlikely to be accepted and applied in real world problems. To tackle this issue, domain experts must find a clever way of visualising and understanding solutions, for example, plotting graphs and performing scenario analysis. Previous work proposed to solve K-MDPs, i.e, given an original MDP and a parameter K, generate a reduced state space MDP with at most K states. State abstractions proved to reduce the complexity and increase the interpretability of MDP solutions and models. However, states aggregated according to algorithms that minimize the loss of performance may not have a meaning for human experts. To bridge the gap between artificial intelligence (AI)-designed state space and human experts, we address the challenge of including human preferences in the state aggregation process. Building on previous work, we define the problem of solving constrained K-MDPs, i.e, generate a reduced state space MDP with at most K states aggregated according to a set of constraints $\mathcal{C}$ specified by a user. We present a new algorithm and assess its performance on two computational sustainability case studies from the literature with one and two state variables respectively. Our results show that we can achieve a substantial reduction on the size of MDP solutions at a small cost of performance, by aggregating states according to user preferences. We have reduced the size of the state space of our case studies up to a 99.75%, with a small loss of performance. Our reduced constrained K-MDP models and solutions are compact and more interpretable. We hope our approach helps reducing the gap between artificial intelligence (AI) systems and human decision makers and increases the uptake of MDPs by improving interpretability and including users in the decision process.

Keywords: *Markov decision processes, interpretability, explainable AI, computational sustainability.*

Participatory modelling for improving flood conditions in migration camps in Boko Haram area, Nigeria

Eskedar Gebremedhin

Institute for applied research in the field of water, subsurface, Deltares, Delft, Boussinesqweg 1, 2629 HV, The Netherlands
Email: Eskedar.gebremedhin@deltares.nl

Abstract: The inclusion of the refugees in the achievement of the Sustainable Development Goal (SDG) has become essential when boosting the development and prosperity while improving dignity of human lives. This new paradigm brings the need to create stronger synergies between the development and the humanitarian context. The United Nations Member States have forged the Global Compact on Migration (GCM) and Global Compact on Refugees (GCR), a historical deal that on the one hand seeks to ease pressures on host countries and communities, and on the other hand aims to support displaced persons in their most immediate needs while at the same time enabling them to build new productive and fulfilling lives.

WASH is often conceived as the primary focus when tackling water-related issues in emergency settings. However, water security in the form of building resilience towards extreme events such as droughts and floods, providing sufficient water for livelihoods and protecting the environment are overlooked. On the other hand, refugee and displacement camps are often located in remote and vulnerable locations within the hosting environment. Lack of resources, time constraints, limited information about the area, poor accessibility and poor safety and protection are common in such complex environments. Ensuring sustainability of such environments, however, requires an inclusive, holistic and human-centred approach.

Participatory modelling (PM) is the process that can lead to such transformation. On the one hand, new adapted methods, models and tools are needed to overcome such obstacles and related complexity. In addition, the engagement of development and humanitarian stakeholders plays an essential role. United Nations (UN) agencies are responsible for camp management. The national and local governments are responsible for selecting the camp location and resource allocation. NGOs support operational activities such as building new wells and providing life-sustaining food.

The project on evaluating the flood conditions and re-designing the drainage network in the Internally Displaced People (IDP) camps in the Boko Haram area, northern Nigeria, is an exemplary case on the use of applying PM in such environments. Accessibility of flood hazard information, knowledge and tools was a prerequisite for transparency and growing a sense of ownership with UN organizations. The preparation, development and use of the models and tools were done in close cooperation and collaboration between the IOM WASH, Deltares team and Red Cross 510. The team made use of globally available open-source data and co-developed the hydrological (HydroMT) and flood models (D-FLOW FM) with the use of local information and knowledge. For those areas that were not accessible, machine learning was used. A dashboard was co-designed to combine stakeholders' information needs and visualize the model results in a tailor-made and easy to understand manner. The system helps reducing water insecurities in the camps in a timely, (cost) efficient, effective and sustainable manner, such as prioritizing and designing effective drainage systems for the IDP camps.

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Keywords: *Flood modelling, participatory modelling, humanitarian emergency, co-design*

Maximising online participatory modelling processes and system dynamics software to enhance health policy decision-making: lessons learned during lockdown

Eileen Goldberg [a] **and Jacqueline Davison** [b]

[ab] *Sax Institute, Sydney, 2037, Australia*
Email: eileen.goldberg@saxinstitute.org.au

Abstract: Policy and program decision makers in Australian government health agencies have recognised the value of a participatory approach to the development of dynamic simulation models of complex high priority topics, such as alcohol related harm, childhood obesity prevention, diabetes in pregnancy. This has been reported within the context of ensuring the modelling process is accessible and transparent to the end-users to facilitate co-production and build trust in models and their outputs as decision-support tools[1]. Such approaches are often limited by the time and resource intense requirements of face-to-face stakeholder engagement, and the practicality of building trust and maintaining ongoing relationships with end-users who may not have been involved in the co-production process.

Online tools and methods created and refined during Covid-19 community lockdowns have been successfully used to enable such participatory approaches for the development of dynamic simulation models in the Australian health sector. These online practices have enhanced the participatory approach, providing unanticipated benefits in terms of accessibility, reproducibility, transparency and cost.

Four case studies will be used to demonstrate the benefits and limitations inherent in such an online participatory modelling approach. These projects were conducted on behalf of public sector agencies in Australia over an 18-month period during 2020-2021. The complex systems modelled covered diverse topics from mental health, to ageing, and digital health record-keeping. A wide range of stakeholders were engaged including policymakers, researchers, health service providers, clinicians and people with lived experiences. The learnings, tools, and innovations from these experiences have utility for participatory modelling processes going forward into the post-Covid 19 lockdown world with an emphasis on flexibility.

In particular, tools supporting interactive and visual communication were of great value in facilitating participatory model development in an online environment. For instance, Miro (miro.com), an online whiteboard platform, was used to adapt Group Model Building activities for online workshops and meetings conducted via teleconference. In addition, maximising use of the functionality inherent in simulation modelling software Stella® Architect (Products (iseesystems.com)) allowed effective, transparent communication and dissemination of the resulting decision-support modelling tools to end-users in both online and asynchronous formats. Innovative development of rich model interfaces incorporating not only well-designed, user-friendly dashboards, but also interactive documentation and visual communication of the entire participatory modelling process and its' outputs arose as a consequence. Information from problem definition and project scoping to model conceptualisation, underlying data and assumptions, model structure and key insights were included in the tools themselves. Consequently, these Cloud-based accessible tools go some way to addressing the need of end-users to engage with and be informed about the methodological choices made during model development, in order to support improved policy-making.

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Keywords: *Participatory modelling, system dynamics, online processes*

Using stakeholder preferences to identify optimal land use configurations

A. Kaim [a] **and M. Strauch** [b]

[a]*Professorship of Ecological Services, University of Bayreuth, Zapf Haus 4, Nürnberger Straße 38, 95447 Bayreuth, Germany*

[b]*Helmholtz Centre for Environmental Research - UFZ, Leipzig, Germany*
Email: andrea.kaim@uni-bayreuth.de

Abstract: Spatial land use allocation is a challenging task. The underlying optimization problems often account for multiple conflicting objectives that can be of different nature (e.g. biophysical or socio-economic). Furthermore, stakeholder preferences are increasingly taken into account. There are different ways how to solve these problems. A priori optimization approaches include stakeholder preferences before the optimization process but this way, the search space is already limited and interesting solutions (i.e. land use configurations) outside this area might not be considered. Interactive approaches, however, require a fast generation of optimal solutions and high stakeholder commitment since the optimization runs multiple times and stakeholders can adjust their preferences iteratively. For both approaches, stakeholders set their preferences without any knowledge about potential trade-offs between the objectives. Therefore, another way is to calculate the set of Pareto-optimal solutions and include stakeholder preferences a posteriori, i.e. after the optimization process. The benefit of this approach is that the whole range of possible land use configurations is evaluated and trade-offs between the different objectives can be analyzed. There are various land use allocation studies that identify the Pareto frontier but, to our knowledge, for all of them it remains open which solutions should be implemented or are preferred by stakeholders. One reason could be that Pareto-optimal solutions, due to their multi-dimensionality, are difficult to c ommunicate. To fill this gap, we developed an a posteriori method that combines Pareto optimization with qualitative stakeholder interviews using the Analytical Hierarchy Process (AHP).

We used the results of a multi-objective agricultural land use allocation problem where each spatial uni can be independently managed according to one of for scenarios: either status quo, business as usual, land sharing, or land sparing. The problem maximizes four biophysical objectives: agricultural production, water quality, water quantity and biodiversity in the Lossa Creek Basin in Central Germany. For the expert interviews we selected eleven local stakeholders with different backgrounds, e.g. water experts, nature conservationists, farmers, etc. In each interview, we informed the stakeholders about the case study area and the trade-offs. These, we visualized using parallel coordinates plots that allowed the stakeholders to browse through the optimal solutions. Then, we applied the AHP that uses pairwise comparisons of the objectives by the stakeholders in order to calculate weights for each of them. With these weights, we selected the preferred solutions from the Pareto-optimal set.

The results show that overall, stakeholders clearly ranked water quality first, then biodiversity, water quantity and agricultural production. Even when comparing different stakeholder groups with each other the ranking remains similar apart from the farmers who put higher weights on agricultural production. The corresponding land use maps show that the overall preferred scenario is the land sharing scenario. Compared to the current status there is no significant change in the spatial distribution of land uses but a huge difference in land management (e.g. less application of fertilizer, more linear elements, no tillage).

The outcomes presented in this study can help decision makers finding land use and land management strategies that fulfil both, biophysical and social demands on the landscape. Especially the combination of qualitative interviews, parallel coordinates plots and AHP shows a way how multi-objective optimization results can be communicated and used for an information-based decision-making process.

Keywords: *Multi-objective optimization, Analytical Hierarchy Process, land use allocation, stakeholder preferences*

Mobilisation of a comprehensive multi-scale evaluation framework for participatory modelling to improve youth mental health policy, planning, and outcomes

G.Y. Lee [a], **I.B. Hickie** [a±], **J. Occhipinti** [a,b±], **Y.J.C. Song** [a], **A. Skinner** [a], **K. Lawson** [a], **and L. Freebairn** [a,b,c]

[a] *Brain and Mind Centre, The University of Sydney, Australia,* [b] *Computer Simulation & Advanced Research Technologies (CSART), Sydney, Australia,* [c] *Research School of Population Health, The Australian National University, Australian Capital Territory*
[±] *Equal contributions*
Email: grace.lee@sydney.edu.au

Abstract: The commitment to include diverse stakeholders in the model building process (participatory modelling) provides opportunities to reflect various expert knowledge and support decision making. Though there is growing interest, evaluation of participatory modelling is lacking, not systematic, or oftentimes, not done at all (Jordan et al., 2018). The complex nature of participatory modelling can be a barrier to conduct evaluations, making it difficult to measure and attribute impact without comparable controls (i.e., 'with participatory modelling' intervention *vs* 'without participatory modelling' control). It is also more common to focus on the final technical model, rather than the participatory processes used to develop the models. Limited time, budget, and stakeholder engagement add additional constraints (Hamilton et al., 2019). This may lead to decreased motivation to conduct thorough evaluations, posing risk of reporting oversimplified outcomes, missing the opportunity to assess its performance to inform the improvement of processes and outcomes. To understand the model development process compared to the actual success or failure of the engagement with the model itself, a comprehensive multi-scale evaluation framework was developed after a scoping review was conducted on participatory modelling evaluation. This presentation will describe how the framework will be mobilised in a youth mental health participatory systems modelling program via the implementation of novel evaluation methods *ex-ante* and *ex-post*. Such methods include the gamification of online surveys to facilitate stakeholder engagement and learning, reduce stakeholder burden, as well as to effectively communicate complex systems challenges at all stages of participatory modelling processes (Figure 1). In the context of youth mental health, participatory modelling evaluation can support to uncover social and technical opportunities, as well as challenges to improve policy, planning and outcomes. The evaluation framework can also be adapted to broader contexts across disciplines internationally.

Figure 1. Mobilisation of a comprehensive multi-scale evaluation framework for participatory modelling to inform the improvement of program processes and outcomes. In the context of a youth mental health participatory systems modelling program, evaluation can uncover social/technical opportunities as well as challenges to improve policy, planning, and outcomes.

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Keywords: *Participatory modelling, evaluation framework, youth mental health, online surveys, gamification*

Participatory system dynamics modelling of groundwater use in India

Pavan Kumar Matham [a], Nagesh Kolagani [b], Supriya Pattanayak [c] and Uma Shankari [d]

[a] PhD Research Scholar, Centurion University of Technology and Management (CUTM), Paralakhemundi, Odisha, India, [b] Professor, Centurion University of Technology and Management (CUTM), Paralakhemundi, Odisha, India, [c] Vice chancellor and Professor, Centurion University of Technology and Management (CUTM), Paralakhemundi, Odisha, India, [d] Farmer, Researcher, Activist, E. Palaguttapalli Gram Panchayat, Chittoor district, AP state, India
Email: nagesh.kolagani@cutm.ac.in

Abstract: The paper models the use of the fast depleting groundwater situation in India, using System Dynamics for modelling and the GIS for visualization. It begins with participatory modelling of groundwater crisis in a south Indian village, using crowd-soruced data on groundwater use, irrigated crops, rainfall, etc.

After calibrating using measured data from other sources, the model results were used to help the case study village community understand the groundwater complexities and visualise the benefits of collectivizing groundwater from various sources within the village boundary. For example, it was observed that sustainable use of groundwater to save approximately 50% of rainfed crops in the worst climatic conditions is possible if the community could limit the extent of the water intensive crops to 12.5% of their usual irrigated area.

It then attempts to extend the model to capture the national groundwater, agriculture, and food scenario. Despite paucity and unreliability of the data available, the model was able to capture broad spatio-temporal variations observed in India.

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Keywords: *Groundwater, rainfed agriculture, system dynamics, South India*

Understanding policy instrument interactions to support the adoption of eco-friendly farming practices in Great Barrier Reef catchments

HJ Mayfield[1], R Eberhard[2], C Baker[3,4,5], U Baresi[2], M Bode[1], A Coggan[6], A Dean[7], F Deane[8], E Hamman[8], D Jarvis[9], B Loechel[6], B Taylor[6], L Stevens[2], K Vella[2] and KJ Helmstedt[1]

[1]School of Mathematical Sciences, Queensland University of Technology, Australia, [2]School of Architecture and Built Environment, Queensland University of Technology, Australia, [3]School of Mathematics and Statistics, The University of Melbourne, Melbourne, Australia. [4]Melbourne Centre for Data Science, The University of Melbourne, Melbourne, Australia., [5]Centre of Excellence for Biosecurity Risk Analysis, The University of Melbourne, Melbourne, Australia.[6]Commonwealth Scientific and Industrial Research Organisation (CSIRO), Land and Water, Brisbane, Australia, [7]Centre for the Environment, School of Biology and Environmental Science, Queensland University of Technology [8]School of Law, Queensland University of Technology, Australia. [9]College of Business, Law and Governance, James Cook University, Australia
Email: h.mayfield@uq.edu.au

Abstract: Water quality on Australia's Great Barrier Reef has declined in the past century, threatening this World Heritage marine area. Agricultural runoff from adjacent catchments in Queensland bears primary responsibility, and governments have encouraged the adoption of environmentally friendly agricultural practices to reduce these impacts. Current policy instruments include regulation of farming practices, offering financial incentives through grants or credit schemes, and providing information and assistance to farmers via either community-based social marketing or specialised agricultural knowledge support programs (extension programs). Although there is some understanding of the effectiveness of individual instruments, there is no over-arching framework of how the instruments interact with each other, and how they are affected by the characteristics of the population, the farming practice, and the instrument itself. The social influences that come into play when farmers make complex management decisions are also rarely considered.

We applied a participatory modelling approach to provide answers to these questions, combining expert knowledge from legal, economic and social sciences. These perspectives were integrated to create a cross-disciplinary Bayesian network that explores the effect of different policy combinations on the adoption of sustainable farming practices in the Great Barrier Reef catchment. A range of stakeholders including practitioners, academics and staff from the Office of the Great Barrier Reef (OGBR) were engaged at several key stages of the design process, including the conceptual modelling stage, and during model validation through scenario analysis. The complexity and interdisciplinary nature of the problem created several challenges, such as finding a common language, selecting a suitable elicitation framework, and managing stakeholder expectations of the model.

The final model was presented via workshops to stakeholders and experts from each discipline, and was widely accepted as a plausible preliminary framework for beginning to understand the nuances and interactions between the different policy instruments. Model behavior was consistent with the expectations of both the government stakeholders, and the subject matter experts who took part in the design process. The development of a model to address complex behavioral responses to policy mixes applied in diverse contexts (industries, farming populations and practices) using an interdisciplinary approach and strong stakeholder engagement has proven to be a pivotal first step in improving our understanding how policy instruments can help facilitate practice adoption.

Keywords: *Environmental policy, Bayesian networks, agricultural practices, socio-ecological systems, participatory modelling*

A systematic process for resolving model-data discrepancies (spoiler: the model isn't always the bad guy)

Katherine R. O'Brien [a], **Matthew P. Adams** [a, b], **Paul Maxwell** [a, c], **Felix Egger** [a], **Holger R. Maier** [d] **and Maria P. Vilas** [e]

[a] *School of Chemical Engineering, University of Queensland, St Lucia 4072, Australia*
[b] *School of Mathematical Sciences, ARC Centre of Excellence for Mathematical and Statistical Frontiers, and the Centre for Data Science, Queensland University of Technology, Brisbane 4000, Australia*
[c] *Alluvium Consulting Australia, 14/36 Agnes St, Fortitude Valley, QLD 4006, Australia*
[d] *School of Civil, Environmental and Mining Engineering, The University of Adelaide, Adelaide 5005, Australia*
[e] *Department of Resources, Queensland Government, Dutton Park 4102, Australia*
Email: k.obrien@uq.edu.au

Abstract: Modelling is typically an iterative process of data collection, model development, refinement of data collection, model refinement, etc. Comparing model predictions with observations is important as a "reality" check of modelling outputs, for assessing whether the model is fit for purpose and for improving model performance.

The processes above rely on the implicit assumptions that data are correct, and that models can be improved through comparison with measurements. However, just as "all models are wrong but some are useful", it can be said that "all data are incomplete, and some are wrong". Mathematical models are only ever simplified representations of the real world, and similarly data provide only a snapshot of what is happening in time and space. In environmental systems, data are rarely available on the spatial and temporal scales which match system variability. Furthermore data, like models, are subject to error, from a variety of sources. Objectively resolving the cause of discrepancies between predictions and observations means recognizing that these differences could arise from either the model… or possibly the data!

This talk presents a framework for characterizing and resolving model-data discrepancies, and includes case studies which demonstrate how models can be used to identify and resolve errors in data, not just vice versa. The framework and case-studies presented here are part of a larger project using inconsistencies between predictions and observations to highlight how integration of models and data can improve decision making. As part of this project, we are exploring barriers to combining insights from models and measurements and will be soliciting audience participation, to help characterize common criticisms about the use of models and data in decision making.

Keywords: *Models, data, integration, barriers, predictions*

INVITED PAPER

EXTENDED ABSTRACT ONLY

Modelling and research to support climate adaptation in the Murray-Darling Basin

David A. Post[1], **David E. Robertson**[2], **Rebecca E. Lester**[3] **and Francis H.S. Chiew**[1]

[1] *CSIRO Land and Water, Canberra, ACT*
[2] *CSIRO Land and Water, Clayton, Victoria*
[3] *Deakin University, Geelong, Victoria*
Email: david.post@csiro.au

Abstract: Many models (GR4J, Sacramento and SIMHYD for example) currently exist to assess the hydrological impacts of climate change. Some models (IQQM, Source) also exist to assess the hydrological impacts of climate adaptation options in regulated river systems. There are a smaller number of models designed to assess the impacts of climate change and adaptation options on socio-economics, the community and the environment more broadly.

A current program of work known as MD-WERP – the Murray-Darling Water and Environment Research Program, seeks to improve the understanding and representation of key processes in hydrological models used to underpin basin analysis and planning. We will work with policy makers and water managers in State and Federal government to apply these models to assess the impacts of climate change and climate adaptation options on hydrological, ecological and socio-economic outcomes in the Murray-Darling Basin. This will allow planners to consider a wide range of adaptation options in the review and revision of the Murray-Darling Basin Plan that is scheduled for the next few years.

The vast majority of global and regional climate models, as well as understanding of changes in global and regional circulation patterns suggest a drier future for the Murray-Darling Basin with consequently more frequent and severe droughts. The adaptation options to be assessed therefore are primarily those that minimise the impacts of drier conditions on the environment, irrigators and the Basin community, along with models that allow assessments of trade-offs between these disparate water users to be made.

The models that are required to assess these adaptation options also need to be diverse, covering not only things such as changes in rainfall and hydrological response, but also climate adaptation options in river system operations, conjunctive use of groundwater and surface water, water trading and allocation, and consequent impacts on the environment, irrigators, basin communities and First Nations groups.

This presentation will provide an overview of MD-WERP with a focus on the climate adaptation and hydrology themes, assessing how modelling tools can be used to better inform Basin-wide water resources policy and planning.

Keywords: *Climate adaptation, climate change, MD-WERP, modelling, Murray-Darling Basin*

How thunderstorms appear in weather forecasts

B. Price and M. Foley

Science and Innovation Group, Bureau of Meteorology, Australia
Email: michael.foley@bom.gov.au

Abstract: Thunderstorms present a range of dangers to the community. Therefore, information about thunderstorms in the Australian Bureau of Meteorology's 7-day forecasts for the public can be important for peoples' decision making. In these forecasts, thunderstorms are described with likelihood-related text phrases such as 'possible thunderstorm' and 'thunderstorm likely'. There is a complex series of steps that lead to the placement of thunderstorms in the forecast. The process, which has been shaped by several historical factors, is linked to the probability of precipitation and involves both human-driven and automated aspects.

The thunderstorm forecasts lack specific explicit quantitative definitions, which makes it hard to assess the quality of the service. However, by measuring the characteristics of the forecasts, informed by knowledge of the production process, we can start to understand the nature of the service currently being provided. We have done this using a complete set of national thunderstorm forecasts issued during Summer (December to February) 2020/2021, comparing these forecasts to thunderstorm observations derived from lightning strike data. This has given a quantitative understanding of what forecasts currently represent, which can inform future decisions around service definitions and improvements to the production process.

From these results, we highlight notable differences that exist in the current service that depend on climatic zones, forecast horizons, and particular offices issuing the forecast. We observe an overall trend whereby the same forecast terms represent increasingly larger storm likelihoods as we move from temperate parts of the country to the tropics. This is driven by climatological factors and local forecast practices. Additionally, we observe a convergence of forecast terms towards the climatological frequency with increasing forecast horizon.

We suggest what a nationally consistent and clearly defined service, driven by thunderstorm probability information, might look like. The findings indicate that moving towards such a service, consistent at the national level, will result in service changes over different parts of the country and different forecast horizons. This poses questions around how the service should be best designed to most effectively support decision making.

Once a thunderstorm definition has been established, forecast skill and accuracy can be measured. This facilitates objective improvement of the forecast production system including determination of where human input does or does not add value to the service, over automated approaches.

Keywords: *Thunderstorm forecast process, probabilistic forecasts, automation, forecast verification*

EXTENDED ABSTRACT ONLY

Identifying minimum information requirements to improve integrated model capabilities: lessons learned from Dynamic Adaptive Policy Pathways

C. Rosello [a], J.H.A. Guillaume [a], P. Taylor [b], S.M. Cuddy [c], C. Pollino [c] and A.J. Jakeman [a]

[a] Institute for Water Futures, Fenner School of Environment & Society, Australian National University, Canberra, ACT, 2601, Australia, [b] CSIRO Data61, Sandy Bay, TAS, 7005, Australia, Australia, [c] CSIRO Land and Water, GPO Box 1700, Canberra, ACT, 2601, Australia.
Email: caroline.rosello@anu.edu.au

Abstract: Integrated assessment models (IAMs) have emerged as common decision support tools when dealing with complex systems. Such models have mostly been used as surrogates of systems to identify "best-guess" solutions. This use has particularly been criticised for its inability to provide information required by decision makers to deal with deep uncertainty. In recent decades, new approaches, defined as robust and adaptive approaches, have emerged to tackle deep uncertainty issues as well as highlight salient information to inform decision-making. Among them, dynamic adaptive policy pathways (DAPP) approaches are of interest in the context of improving the relevance and legitimacy of models to tackle deep uncertainty issues and the credibility of their outputs.

The purpose of this research is to present a heuristic and reflective methodology based on the identification of minimum information requirements to 1) represent salient information for decision-makers and 2) identify solutions to better represent that information in the modelling process. The proposed methodology builds on lessons identified from the DAPP framework to consider mental models and their influences on the representation of a problem of interest, as well as to manage deep uncertainty in IAMs. Based on the identification of requirements to apply the DAPP framework, a heuristic and reflective approach was developed to identify information gaps in IAMs, and guide reflection about solutions, either inferred from an IAM itself, involving the developers, or both. We use the Basin Futures tool, a new cloud based IAM for entry-level surface water resources assessment, as a case study to setup the approach and illustrate its potential in the context of the Brahmani River Basin, India.

Results from the approach demonstrate the interest of considering a minimum information requirement framework and the application of the heuristic and reflective methodology to customise existing IAM and improve their ability to better represent a system of interest and associated problem at stake for decision-makers, modellers, and other stakeholders, as well as to consider means to adjust the DAPP framework to manage deep uncertainty issues. Another benefit of the approach is to reduce modelling blindness associated with societal responses to changes. By addressing finer scale decisions, in addition to macro-scale ones, the approach raises awareness of potential issues associated to decisions, and supports reflection about the reciprocal influence and implications of decisions and human factors on the ability of an adaptive plan to successfully achieve a sustainable vision for a system of interest.

Overall, central to the approach is a collaborative modelling setting, bringing together stakeholders, modellers, and developers. How the approach could contribute further to foster collaborative modelling and decision-making as well as be transferable to a broader range of IAMs can considered in future applications in real decision-making contexts.

Keywords: *Adaptation pathways, salient information, decision support, model customisation*

How evolution of democracy can open new horizons for participatory modeling

A.A. Voinov [a]

[a] *Centre on Persuasive Systems for Wise Adaptive Living (PERSWADE)*
Faculty of Engineering & IT, University of Technology Sydney
Email: aavoinov@gmail.com

Abstract: There is growing interest in new forms of democracy, largely fuelled by obvious failures of the traditional democratic institutes and approaches, as we know them. There is much frustration in lack of representation in the current elected bodies, which are seen as elitist, manipulative, engaged in cronyism, corruption and largely driven by the self-interests of the wealthy. There are opinions that democracy is already becoming a plutocracy, when the "one person – one vote" principal is substituted by the "one dollar – one vote" mechanism. While there is much truth in these concerns, it becomes only more important to seek for alternatives. One such development that is becoming increasingly popular in some European countries is the idea of direct citizen participation in governance, through such mechanisms as citizen panels, citizen consultations, civil deliberation, citizens' assemblies, "preferendums", etc.

In all these new forms of democracy we can find a lot of resemblance to what Participatory Action Research (PAR) in general and Participatory Modelling (PM) in particular has been advocating for over quite some time already. One of the advantages of using PM in these processes is that we can directly link to some of the latest advances in information technologies and social media. There are many ways, in which PM could enrich and contribute to the civil deliberation process, including the following:

- PM provides a well-tested and functional mechanism to facilitate discussions, using the modelling process to structure the process and to put together multiple facts and opinions in a systemic way that is easier to communicate and understand. The systems approach essential in modelling offers a common language to discuss and frame potentially controversial problems.
- PM can seamlessly connect qualitative ideas (mental models) of individuals and groups and further link them to quantitative results that can be produced by computer simulations and model analysis. This is instrumental to communicate and demonstrate the uncertainties involved in the systems at stake. This can help to take us from the "hand waving" and arguing stage to facts, numbers and statistical analyses.
- New tools developed in the context of PM use modern communication tools (social media and online sources) to create massive bottom-up platforms and mechanisms for deliberations based of social engagement and learning. For example, Discussoo.com provides a platform for moderated online discussions, where comments are further processed using AI algorithms to elicits mental models of stakeholders. While citizen panels are usually limited to 100 or so participants, using such tools we can provide for almost unrestricted participation by all engaged stakeholders. The deliberations can be further enriched with AI selected relevant information extracted from the web.

At the same time, there is much we can learn from the civil deliberation processes that are already taking place to advance and improve the tools and methods that are used in PM and that could be making PM even more useful for the alternative democratic processes. We should be also aware of the new ethical problems that can arise when AI is becoming even more involved in citizen discussions, and will have to create effective barriers for misuse, fake news, and further manipulation.

Keywords: *Decision making, communication, civil deliberation, citizen consultation, alternative democracy*

Design of experiment in participatory modelling

Fateme Zare[a] and **Sondoss Elsawah**[a]

[a] *Capability Systems Centre, University of New South Wales, Canberra, Australia*
Email: f.zare@adfa.edu.au

Abstract: Design of experiment for problem-solving simulation is the process of formulating a plan to gather the desired information at minimal cost and enable the analyst to reach valid conclusions (Shannon, 1975) and involves designing a unique combination of independent, dependent and control variables and planning to examine the experiments with the available simulation model. Therefore, experiments generate insight into the causal relationship between different elements and models' operation (Chakladar, 2016). In other words, experiments help modellers to understand how properly use the model to answer stakeholders' questions. Design of experiment is a critical decision fork that could change the whole modelling pathway, notably, the model results and, consequently, policies that will be made based on the model results. Therefore, a proper design of experiments (DOE, Designed Experiments or Experimental Design) develops knowledge and should be reliable, replicable, and valid.

However, the design of experiment depends on the modellers' perception of the problem and their skills in translating it into mathematical variables and equations. Besides, decision-makers and stakeholders communicate their needs in words while modellers use variables and data to analyse the system. Therefore, it is critical and challenging in participatory modelling to translate decision-makers questions and concerns into modelling experiments, examine them, and communicate effectively with decision-makers about the experiments.

Despite its significant role in the model results' accountability and applicability, the role and procedure of design of experiment are not extensively and effectively investigated in the participatory modelling process. This paper illustrates the importance and effect of a well-designed experiment in participatory modelling to answer the stakeholders' needs. Also, we discuss the link of design of experiment step within a participatory modelling process to assist modellers in designing efficient and fit for purpose experiments to increase the transparency and repeatability of the research.

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Keywords: *Design of experiment, participatory modelling, experimental setup, decision support*

Socioeconomic scenarios of water futures in the era of uncertainty and change

Baihua Fu [a], Wendy Merritt [a], Caroline Rosello [a], Serena Hamilton [a], Carina Wyborn [a], Joseph Guillaume [a], Jenny Riches [b], Sarah Stevens [b] and Anthony Jakeman [a]

[a] *Institute for Water Futures and Fenner School of Environment & Society, The Australian National University, Canberra, ACT 2601, Australia*
[b] *Department of Environment and Science, Brisbane, Queensland, Australia*
Email: baihua.fu@anu.edu.au

Abstract: Water resource management operates within a complex system of interactions between the biophysical systems (including climate, land and water) and socioeconomic systems. Current monitoring and modelling approaches are useful for exploring "what-if" scenarios based on past, linearly extrapolated knowledge. But they are ill-equipped to anticipate how the environment will respond to a wider range of plausible dynamics and accelerating socioeconomic changes in the medium to long term, especially given we are facing an era of uncertainty and rapid change.

Foresight is a systematic and participatory process for looking to, thinking about, and debating the future. It is not a way to predict the future; rather it is a way to uncover perspectives on the many different futures that could happen and to use those perspectives to make decisions today. Foresight has emerged as a field of study and practice to help conceptualize and facilitate dialogue to anticipate or prepare for future changes, and has been used in public policy development and enterprise strategic planning. While scenario development can take many forms, the Shared Socioeconomic Pathways (SSPs) are one example from the climate research community developed to explore how socioeconomic factors may change over the next century, thereby how the world might evolve under different levels of climate change mitigation (Riahi et al., 2017). These scenarios have been used in the latest climate modelling (CMIP6) for the IPCC's sixth assessment report, and play a role in climate policy discussions.

The Queensland Water Foresight Project was initiated in 2020 to develop processes and tools to co-create plausible futures for Queensland's water quantity, quality and related ecosystems, and identify opportunities and interventions to move towards desirable outcomes for water and beyond. Four scenarios are being explored through desktop research and stakeholder workshops with participants from sixteen organisations including Queensland local and state governments, Natural Resource Management bodies, water industries, consultancies and universities. These scenarios explore possibilities around common core assumptions:

- *Agriculture Transformation* describes a future with strong water and carbon credit markets. Significantly drier and more volatile climate leads to the transformation of the agriculture sector, including the rise of controlled-environment and cellular agriculture.
- *Sustainability Transition* describes a future driven by the public and organisational change towards sustainability. Strong acceptance of science and collaborative, integrative and proactive water management are the norm.
- *Decentralisation* describes a future with more decentralised population and infrastructure and where water management focuses on local interests and community participation.
- *Vested Interest* describes a future where economic growth drives decision making. It features distrust in science, big grey infrastructure, environmental degradation and social conflicts.

The scenarios will be used to test the robustness of the strategies and identify intervention pathways of water management. They will also be used to support the development of forward-looking science agenda, including identifying pathways for research and modelling to support future-oriented decision making.

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Keywords: *Water management, futures, foresight, scenarios*

What will Industry 4.0 and irrigation modernisation mean for water modelling in 2050?

SK Hasnain [a], **JHA Guillaume** [a], **ME Qureshi** [a], **A Ross** [a] and **AJ Jakeman** [a]

[a] *Institute for Water Futures and Fenner School of Environment & Society, The Australian National University, Canberra, ACT 2601, Australia.*
Email: sunail.hasnain@anu.edu.au

Abstract: Today, there is much interest and inevitably some hubris around the Industry 4.0 revolution in many walks of life. Modelling in its various forms has been an ever-increasing backbone of this journey starting from late 1700's when the 1st industrial revolution began. Now momentum for a 4th industrial revolution is building. This revolution utilises electronics and information technology, such as SCADA and robots working within a Cyber-Physical System (CPS), including in the context of precision and digital agriculture (De Clercq et al., 2018; Zambon et al. 2019).

The water sector has started to embrace this revolution but there is opportunity for it to play a stronger role. Water requirements are likely to increase rapidly in order to produce food for a possible future population of some 8 billion in 2025 and 10 billion in 2050. Corresponding increase in value of water motivates investment and calls for preparedness for future modelling and information requirements.

In agriculture and irrigation, a tripartite of data base, knowledge base and model base provides the foundation for monitoring, control, prediction and logistics. With emphasis on farm management, *Monitoring* will encompass weather, soil, crop and water monitoring. *Control* will broadly include precision irrigation systems, fertilisation, crop pest and disease control, and smart farms having automatic harvesting systems. *Prediction* will include weather forecasting, crop development, yield estimation and global market demand. And *Logistics* will create a suite of autonomous vehicles and remotely operated farm machinery.

With this vision of tripartite bases and tetra domains, a holistic framework is conceptualised to describe pathways to harness technology, enhance management practices, deal with challenges of food production, embrace modernisation, streamline change and to be open to innovate sustainable solutions. This proposed framework consists of nine interrelated elements which are Finance, Socioeconomic, Process, Governance, Risk, Investment, Technology, People, and Innovative methods of water use.

Finance and socioeconomics will make greater use of big data and data science. Telemetry, remote sensing, and other technologies will reduce site attendance to measure and/or adjust water flows. Seasonal forecasts are expected to become reliable enough to predict future water availability. Skills capabilities will accordingly benefit from new training and assessment methods as well as a whole of labour force perspective. Vendor management systems can be used to help find the best product and professional services from all over the world. Training needs analysis for teams would be well understood from end to end for a farm for the whole lifecycle. Today's innovations such as managed aquifer recharge, rainwater harvesting and use of recycled water will become easier to deploy. Increased data will support not just predictive maintenance of irrigation infrastructure but also more sophisticated water security risk management and investment approaches.

A questionnaire is under preparation to assess farmers' current status in relation to the nine elements using Likert, Binary and Multiple-Choice scales, with evaluation of its reliability and validity. The resulting scale will assign an overall category and sub-categories to a farm for each element and catalyse discussion around farm management. Semi-structured interviews will make use of radar plots for comparison among farms, seek feedback on the categories as well as framework elements, and examine farm readiness for modernisation, potential improvement, sharing of knowledge, enhancing existing research and opportunities for customised solutions at farm level.

Keywords: *Modernisation, irrigation innovation, challenges of 2050*

National Hydrological projections for Australia: using storylines to communicate plausible future risk to water sensitive communities

Vjekoslav Matic[a], Ulrike Bende-Michl[a], Louise Wilson[b], Annie Hogben[a], Pandora Hope[a], Greg Kociuba [a], Sri Srikanthan[a], Margot Turner[a], Alison Oke[a] and Zaved Khan[a]

[a] *Bureau of Meteorology, Australia*
[b] *UK Meteorological Office, UK*
Email: Vjekoslav.matic@bom.gov.au

Abstract: Hydrological Projection results feature many sources of uncertainty, including how future greenhouse gas emissions will develop, highly uncertain changes to atmospheric circulation, how a warmer climate will lead to changes to hydrological and climate interactions, as well as the ability of climate and hydrologic models to represent relevant processes. For these reasons, communicating projections and uncertainties is increasingly complex, and presents significant challenges when attempting to describe a change of a hydrologic or climate feature in probabilistic terms. A storyline approach, a description of an internally consistent evolution of plausible future events, provides a way to focus on only assessing uncertainties that relate a specific impact of interest. A set of storylines representing the range of plausible changes related to an impact can be used to explore climate change projections.

The National Hydrological Projections (NHP) consist of 16-ensemble members using 4 Global Climate Model (GCMs) and one Regional Climate Model (RCM) that are downscaled and bias-corrected using 3 different methods. Climate forcing from these models are used to run the Bureau's operational AWRA-L model (Frost and Wright, 2018) to derive future water balance items (soil moisture, runoff and potential evapotranspiration). We use the NHP to assess changes to future water security by applying the storyline concept. Storylines are particulalry suitable for investigating changes to water security, since they can represent interactions of multiple variables i.e. changes to supply and demand. In the example of the Wet Tropics NRM region in Northern Australia, almost all storage infilling occurs in wet season and so modelled wet season runoff is used an indicator for storage infilling (and hence supply). Soil moisture in the dry season are used as an indicator to changes in demand behaviours associated with irrigation to agriculture and consumptive use.

Four storylines for changes water security in 2050 were identified 1) Large decreases to wet season runoff (-35%) and decrease to dry season soil moisture (-7%). 2) Very large decreases to dry season soil moisture (~22%), increases to wet season runoff (10%) 3) Little change to both dry season soil moisture and wet season runoff and 4) Large increase in wet season runoff (50%), with little change to dry season soil moisture. Storyline 1 and 2 represent supply decreases, with increases and no change to demand respectively. Storylines 3 and 4 represent no climate driven changes to demand, however increases in demand from population growth could see water security challenges. Storylines 2 and 4 project increases to runoff, however this will not result in improved water secruity without additional storage capacity since storages reliablly fill each year under current conditions. Therefore storyline 4 could see lower water secruity in the future.

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Keywords: *Climate change, water resources, water security, climate change impacts*

Lessons from uncertainty management of the Basin Plan surface water Sustainable Diversion Limit

Leila Noble, [a] **Joseph Guillaume,** [a] **Carina Wyborn,** [a] **and Anthony Jakeman** [a]

[a] *Institute for Water Futures and Fenner School of Environment & Society, Australian National University, Canberra, Australia*
Email: leila.noble@anu.edu.au

Abstract Uncertainty is always present and often pervasive in decisions about how to allocate limited water resources. Uncertainty from models affects decisions in complex ways. A better understanding of existing practices for addressing uncertainty in water management decisions, which are often unclear, can help towards modelling processes that better support decision making under uncertainty in future. This research looked at a case study, aiming to understand how uncertainty in models influenced the Australian Government's decision-making process leading to the establishment of the highly contested 'sustainable diversion limit' (SDL) for surface water. The SDL limited the volume of water that can be extracted from the Murray Darling Basin with the aim of improving environmental outcomes. It is an example of a decision involving modelling, competing water users and multiple government and private actors. The decision-making process spanned several years and drew on knowledge and models that included many gaps and uncertainties, some of which will always exist since they relate to variability in the system.

To analyse the case study, I used an 'argument map' generated through systematic document analysis to provide a representation of the reasoning presented in government reports and legislation relating to the SDL. Eight semi-structured interviews, with interview questions informed by the argument map, provided perspectives from people who had knowledge of the decision-making process, including insights into the reasons for decisions. The ways in which decision makers dealt with uncertainty fell into four themes that yield recommendations for modelling in the future.

First, decision makers framed their decision in the context of adaptive management, with the implication that the original modelling and decision did not need to attempt to address all uncertainties. However, concerns from interviews about institutional and external barriers to adaptive management suggest that this approach to uncertainty needs a substantial investment to understand, and develop, the capacity needed to adapt.

Second, the legislative mandate to use the 'best available science' nonetheless left many unresolved uncertainties in relation to the original SDL. Notably, the process largely used existing data and models, which may not have been fit-for-purpose, and did not explicitly include climate change projections, with uncertainty as a possible reason for excluding them. There is a need to plan and target investment in models to ensure that the best available science is sufficient for future purposes and that the uncertainties are assessed.

Third, these unresolved uncertainties created a space for political pressure to limit water recovery for the environment in favour of socioeconomic outcomes. For example, government reports stated that uncertainty was a reason for setting more flexible targets to be achieved within the models under the chosen SDL volume but this led to decreases in water for the environment.

Fourth, the connection between the scientific models and the final decision lacked adequate transparency in relation to uncertainty. While the technical reports provided some detail, interview participants argued that the Australian public generally overestimates the certainty in the outcomes due to limited communication about uncertainty. There were also concerns with the quality of community engagement. Decisions made on the basis of politics, rather than an assessment of scientific uncertainty in modelling of the system, are only legitimate when good governance principles are adhered to. This includes transparency and opportunities for democratic influence, including participation in the modelling process. Although the SDL was framed as an evidence-based decision, modelling processes and scientific knowledge alone would never have been able to generate a consensus SDL volume. The magnitude of uncertainty in the outcomes and the complex responses to uncertainty need to be more transparent and better understood, including by decision makers and communities, to better support future decision-making processes under uncertainty in 2050.

Keywords: *Uncertainty, sustainable diversion limit, good governance*

‘Him makeum walk straight’: using simulation to explore Australian Aboriginal skin groups

A.H. Dekker

Dekker Consulting, P.O. Box 3925, Manuka, ACT, 2603, Australia
Email: dekker@acm.org

Abstract: In Dekker (2019), while arguing for the use of agent-based computer simulation as a tool for understanding the function of anthropological phenomena, we explored the system of 8 “skin groups” or “subsections” used across central northern Australia (Figure 1). We noted in passing the well-known fact that this system has the structure of the dihedral group D_4. In this paper, we address the question: why D_4? We report further analyses and NetLogo-based simulations comparing this system against alternative structures derived from group theory, and show that this system based on D_4 was indeed better than the alternatives: genetically, in story transmission, and with regard to formal properties. Table 1 summarises our findings.

Table 1. Comparing the “subsection” system of 8 Aboriginal skin groups against four alternatives

System		Spousal symmetry	Paternal 2-cycles	Distinct grandparents	Genetic benefits	Story preservation
D_4 (system actually used)		✔	✔	✔	✔✔	✔
Alternatives	Z_8	–	✔	–	✔✔✔	–
	Z_8(b)	–	–	–	✔	–
	$Z_2 \times Z_4$	–	✔	–	✔	–
	Q_8	–	–	–	✔	–

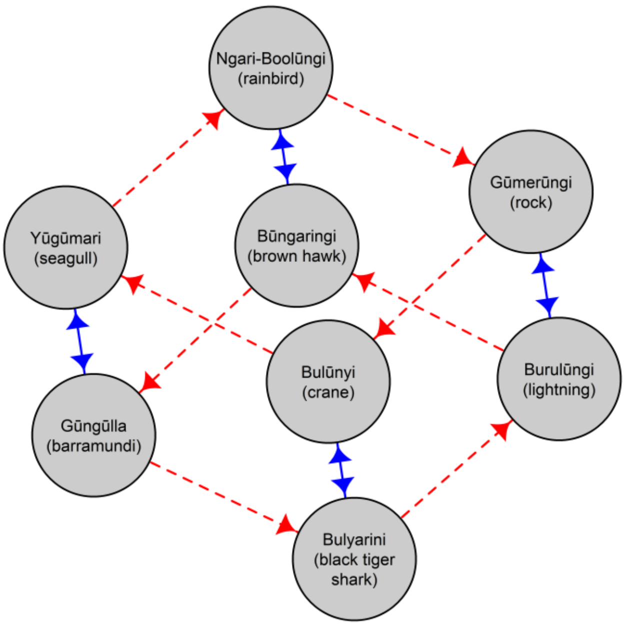

Figure 1. The 8 skin groups (“subsections”) of the Lardil people. Single-headed red arrows run from mother to child (μ), and double-headed blue arrows run between father and child (ϕ). Note that $\mu^4 = \phi^2 = i$ (where i is the identity).

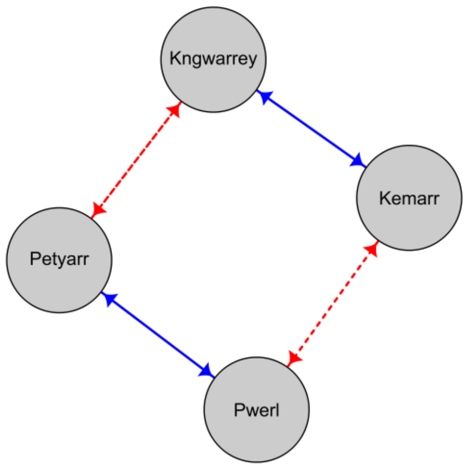

Figure 2. The 4 skin groups (“sections”) of the Alyawarr people. Dashed red arrows run between mother to child (μ), and solid blue arrows run between father and child (ϕ). Valid marriages are vertical or horizontal, i.e. Kngwarrey with Pwerl and Petyarr with Kemarr. Note that $\mu^2 = \phi^2 = i$.

Keywords: *Agent-based modelling, NetLogo, Anthropology, Skin groups, Aboriginal culture*

Understanding Eurovision tele-voting through modelling

A.H. Dekker

Dekker Consulting, P.O. Box 3925, Manuka, ACT, 2603, Australia
Email: dekker@acm.org

Abstract: The Eurovision Song Contest has been held since 1956, providing European countries an opportunity to vote on other countries' songs. Voting has long been controversial, however, with accusations of unfairness and collusion. In this paper we model the tele-voting by members of the public in the most recent (2021) competition. Our goal is to determine to what extent a simple model with known factors can explain the results. Our model is based on five factors, three of which apply to some countries only:

- Quality-based (Q) voting
- Expatriate (α) voting (people in country A with ancestry from country B voting for country B)
- Nordic (β) voting (some countries only)
- Singer-based (γ) voting (some countries only)
- Covid-based (δ) voting (some countries only)

We simulated the voting for a sample of 15 countries. Table 1 summarises our results. Our main measure of performance was the mean absolute error in simulating actual tele-voting scores from the event. The mean absolute error was 20.7, with the best match to real data being Norway, and the worst being France.

The performance of the model suggests that no large additional factors contribute to the voting outcomes, although a better fit to the real data would be obtained by explicitly modelling differences in taste between countries and by having a better model of how likely expatriate voters are to vote for their "home country."

Table 1. Experimental results

Voting Country	Country Cluster	Model	α votes	β/γ/δ votes	Absolute Error	R^2
Norway	Nordic	$\mathbf{Q} + \alpha\ \mathbf{E/G} + \beta\ \mathbf{X}_{\text{Nordic}}$	16.5%	13.9%	8	96.2%
Spain	–	$\mathbf{Q} + \alpha\ \mathbf{E/G}$	8.3%		12	93.7%
Israel	–	$\mathbf{Q} + \alpha\ \mathbf{E/G}$	15.6%		12	91.3%
Latvia	Western	$\mathbf{Q} + \alpha\ \mathbf{E/G} + \beta\ \mathbf{X}_{\text{Nordic}}$	41.6%	9.9%	16	89.6%
Greece	Greek	$\mathbf{Q} + \alpha\ \mathbf{E/G} + \gamma\ \mathbf{X}_{\text{Singer}}$	8.4%	8.1%	16	85.9%
Denmark	Nordic	$\mathbf{Q} + \alpha\ \mathbf{E/G} + \beta\ \mathbf{X}_{\text{Nordic}}$	10.0%	24.9%	16	83.2%
Australia	Western	$\mathbf{Q} + \alpha\ \mathbf{E/G} + \delta\ \mathbf{X}_{\text{Covid}}$	11.1%	15.4%	18	80.4%
Slovenia	Balkan	$\mathbf{Q} + \alpha\ \mathbf{E/G}$	18.5%		22	72.7%
Cyprus	Greek	$\mathbf{Q} + \alpha\ \mathbf{E/G} + \gamma\ \mathbf{X}_{\text{Singer}}$	11.4%	5.7%	22	73.9%
Switzerland	Balkan	$\mathbf{Q} + \alpha\ \mathbf{E/G}$	50.0%		24	76.7%
Netherlands	–	$\mathbf{Q} + \alpha\ \mathbf{E/G} + \gamma\ \mathbf{X}_{\text{Singer}}$	0%	6.8%	26	55.0%
Czech Republic	French	$\mathbf{Q} + \alpha\ \mathbf{E/G}$	47.8%		28	67.4%
United Kingdom	–	$\mathbf{Q} + \alpha\ \mathbf{E/G} + \delta\ \mathbf{X}_{\text{Covid}}$	10.5%	16.4%	28	66.9%
Germany	Western	$\mathbf{Q} + \alpha\ \mathbf{E/G} + \delta\ \mathbf{X}_{\text{Covid}}$	5.0%	17.3%	30	70.1%
France	French	$\mathbf{Q} + \alpha\ \mathbf{E/G}$	17.3%		32	62.8%
Mean					**20.7**	**77.7%**

Keywords: *Voting, Eurovision, Stochastic modelling*

Designing collaborative intelligence teams for agility in an envisioned command and control world

Rebecca Ong[a] and Neelam Naikar[a]

[a] *Defence Science and Technology Group*

Email: Rebecca.ong@dst.defence.gov.au, Neelam.naikar@dst.defence.gov.au

Abstract: Analysis of future trends has indicated a shift towards faster, more uncertain, and newer forms of conflict within the next few decades. In order to contend with threats in this envisioned world, the Australian Defence Force (ADF) has identified the need for more agile structures to facilitate rapid and effective adaptation to unpredictable and degraded situations; standing as a significant change from the current hierarchical command and control (C2) structure. Within this context, the integration of agile human-artificial intelligence (AI) teams into the future force has been identified as a key area of development. This concept is known as 'Collaborative Intelligence' (Naikar, Moy, Kwok & Brady, 2021).

Current AI design is typically based around specific scenarios—an approach which can underestimate the flexibility necessary to operate in contested military contexts and may exclude the capabilities or advantages of humans involved in unpredictable situations. These methods can, and have historically, led to brittle technology unable to cope with unexpected or rapid situational changes, resulting in low adoption rates of intelligent technologies in the military (Coombs, 2019). The uncertainty and unpredictability of the future contested environment is expected to amplify these effects, necessitating novel design approaches.

Cognitive Work Analysis (CWA) is suggested as a powerful and systematic design approach to these problems (Naikar et al., 2021). Unlike traditional methods, which normally dictate 'which actors should do what' based on predefined situations, CWA outlines the system in terms of its constraints or boundaries on successful action. As such, prescribed routes to a goal are not defined and actors are free to choose from many credible possibilities within the boundaries of the system; intrinsically weaving agility through the design. Importantly, this analysis defines the system independently of specific actors, so that both human and artificial intelligence can be accommodated. This type of design approach facilitates fluid distribution of tasks throughout the system, acting as inbuilt redundancy and resilience to disturbances.

In this study, we present a novel approach to human-AI team design using CWA. As a first step, analysis of authoritative documents and subject matter expert interviews were conducted to extract key themes, problems, and outcomes present in the envisioned world. This work resulted in a textual description and graphical representation, which succinctly define the context for future designs. Using this description, the first dimension of CWA, Work Domain Analysis (WDA), was applied to begin outlining the fundamental boundaries of a C2 system. This work provides an analytical framework and visualisation onto which C2 elements in the ADF can be mapped, facilitating greater understanding of critical relationships, concepts and C2 needs within this context. In addition, the model identifies and defines boundaries to which the C2 system and consequent collaborative intelligence teams must adhere.

This research crystalises the potential challenges faced in the future operating environment and defines the fundamental context for eliciting design requirements for agile C2 systems. As the boundaries identified are independent of situation or specific hardware, they are globally applicable to ADF C2 elements and facilitate less brittle design by preserving environment unpredictability and flexibility of action. The level at which the WDA has been developed also allows it to be widely applied as an aid in Agile C2 analysis. Moreover, this approach can be extended for application in design of technologies other than human-AI teams.

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Keywords: *Cognitive work aalysis, Agile C2, Human-machine teams, artificial intelligence*

A discrete event simulation for modelling Aljamarat Bridge rituals and evacuation scenarios

A.A. Owaidah [a], D. Olaru [b], M. Bennamoun [a], F. Sohel [c, a] and R.N. Khan[d]

[a] Department of Computer Science and Software Engineering, The University of Western Australia, Perth, WA 6009, Australia, [b] Business School, The University of Western Australia, Perth, WA 6009, Australia, [c] Discipline of Information Technology, Murdoch University, Murdoch, WA 6150, Australia, [d] Department of Mathematics and Statistics, The University of Western Australia, Perth, WA 6009, Australia.

Email: almoaid.owaidah@research.uwa.edu.au

Abstract: Hajj is the largest mass gathering event globally that occurs annually. It is a pilgrimage that lasts for about a week. The pilgrims perform rituals at different sites (The Grand Mosque, Mina, Arafat and Muzdalifah) in the city of Makkah, Saudi Arabia. Safety of the pilgrims is number 1 priority for the Saudi authorities and several new projects have recently been completed at the Hajj sites with a goal to improve proceedings. One of these projects was the redesign and construction of the Aljamarat Bridge at Mina City. This project was commissioned to mitigate severe crowd incidents at the bridge in previous years. The new bridge has greatly improved safety of pilgrims. However, unexpected hazards and accidents such as fire or gas leaks can occur, necessitating the evacuation of pilgrims from the bridge. This paper presents a model and simulation study of pilgrim evacuation from Aljamarat bridge using a Discrete Event Simulation (DES) tool called "ExtendSim". The tool was validated by modelling and simulation of three million pilgrims based on a strict scheduling system that distributes them on each level. Based on our methods of allocating specific evacuation routes at each level on the bridge, the evacuation modelling shows promising results when using six towers, resulting in a smooth process without any crowd buildup.

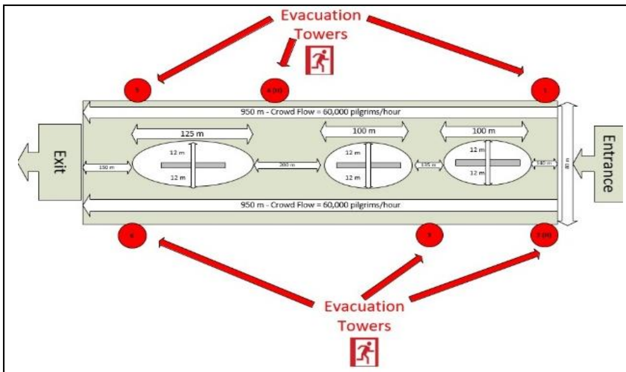

Figure 1. Aljamarat Bridge features (in a level) (Authors' elaboration)

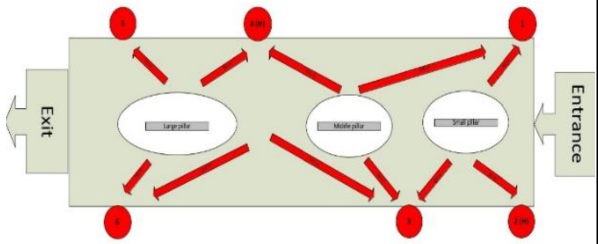

Figure 2. Evacuation exits and pathways (Authors' elaboration)

Keywords: *Hajj, Aljamarat Bridge, crowd management, Discrete event simulation, evacuation modelling and simulation*

The Lobster Game: Experiential learning of system dynamics through serious gaming

R.G. Richards [a,b] **and N. Jagdish** [c]

[a] *School of Business, The University of Queensland, Brisbane, QLD 4072, Australia,* [b] *Coastal and Marine Research Centre, Griffith University, Gold Coast Campus, QLD 4222, Australia,* [c] *BTN Pte Ltd, Singapore.*
Email: r.richards@business.uq.edu.au

Abstract: We showcase a serious game (*The Lobster Game* https://lobstermodel.web.app/) that was developed to help meet the learning objectives of a course (System Dynamics) taught at the University of Queensland Business School (UQBS), Queensland, Australia. This paper presents the motivation for gamifying a system dynamics model and the mechanics of the system dynamics model itself. *The Lobster Game* is a computer-based app (PC, Mac) aimed at helping students enrolled in this course to better understand and apply the concepts of systems thinking and system dynamics. This app was also developed with the capacity to be used in courses from other disciplines within the UQBS including *International Business, Supply Chain Management* and *Sustainability*. The motivation for using a serious game approach was its capacity to foster experiential activity-based learning, moving away from the standard didactic approach. Serious games, which we broadly define here as 'video games with a learning purpose', are growing in global popularity, reflecting the increasing ubiquity of video gaming, the accessibility and utility of powerful video game development software, and the demand for active-based education. The scope was to represent a well-managed fishery dominated by international exports, where fishing effort was regulated but also strongly influenced by market dynamics. The result is a system dynamics model (SDM) developed in Unity3D that draws heavily upon elements of the Australian rock lobster fishery, particularly the western rock lobster (WRL) fishery. Features incorporated into the underlying SDM is an international supply chain of live lobsters, the use of fishing quotas (catch-quota controlled) and supply-demand-price dynamics. The SDM is dominated by balancing loops (8) that provide strong regulating effects on this social-ecological fishery system through ecological (carrying capacity), economic (supply-demand-price, CPUE) and regulatory (quota) feedbacks. Assessment of the SDM's performance involved standard system dynamics tests of unit consistency checks, extreme condition testing, conservation of material and behaviour consistency checks. Consistent with the stated learning objective and its specific application in system dynamics education, *The Lobster Game* contains a story that provides the narrative for the system, and a model, that provides the numerical playground for the system. *The Lobster Game* was completed June 2021 and will be introduced to students during second semester (July - October), 2021.

Keywords: *The Lobster Game, Serious games, video game software, system dynamics, experiential learning, lobster fishery, UQ Cases*

Assessing the effects of natural data variability on predictions of coastal wetland vulnerability in SE Australian

Angelo Breda [a], Patricia Saco [a], José Rodriguez [a] and Steven G. Sandi [a]

[a] *Centre for Water Security and Environmental Sustainability and School of Engineering, University of Newcastle, Callaghan, 2308, Australia*
Email: angelo.breda@newcastle.edu.au

Abstract: Assessments of coastal wetland vulnerability frequently use average values of water level and sediment input, disregarding short and long-term variations. The expensive computational cost of using observed time series is one of the main reasons for such simplification. However, only observed series contain short-term variations (such as severe storms) and long-term interannual variability induced by climate and ocean phenomena. In this work, we used a high-performance computer to carry on simulations with observed and synthetic high-resolution data sets to account for both type of variations.

The study was divided into two parts. In Part I, a simulation using gauged water levels and satellite-derived sediment concentration from 2002 to 2011 was conducted to assess the capability of the modelling framework (Breda et al., 2021) to reproduce in situ measurements of soil elevation change in a wetland of SE Australia. In Part II, a Monte Carlo (MC) approach was used to generate 100 simulations of 100-year duration using input data randomly sampled from 13 years of records (Mar/2002-Mar/2012 and Feb/2018-Feb/2021). Each simulation covers the period between 2000 and 2100, and includes increases in SLR following RCP8.5. The results were compared with simulations using sinusoidal waves and constant sediment concentration, which are typical simplified inputs.

The results of simulated soil elevations obtained in Part I successfully reproduced those from in situ measurements (Rogers et al., 2013), including the observed higher accretion values during years with severe storms. Large spatial variability was observed in simulations, which might be related to differences between the hypothetical (simulated) wetland and spatial complexity of the real site. The results from the MC simulations highlighted regions of higher uncertainty in vegetation evolution. The presence of mangroves in lower areas varied considerably between the MC realisations. However, the elevation change computed in these areas did not vary significantly between simulations. Mangrove encroachment over saltmarsh increased with the rate of sea-level rise (SLR). Soil-elevation change in this area varied considerably. Saltmarsh extension was not altered when upland areas were available for migration, although the variability of the transgression extent was high.

Comparison against MC outcomes using simplified inputs also showed significant differences. The predictions using simplified sinusoidal waves present a larger occurrence of mangrove in lower lands and a much smaller saltmarsh extension than in the results from the MC approach. Predicted soil elevations also differ, being consistently lower when adopting a single wave corresponding to mean tidal range conditions. Nevertheless, the simulations using simplified mean tidal conditions were able to capture the main trend of the MC results.

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Keywords: *Coastal wetlands, environmental data variability, eco-geomorphological modelling, sea-level rise*

Monitoring riverine tree vegetation condition using in-situ evapotranspiration, remote sensing and machine learning

T. M. Doody[a], S. Gao[a,b], J. L. Pritchard[a], M. J. Davies[c], M. Nolan[a] and R. W. Vervoort[d]

[a]CSIRO Land and Water, Waite Campus, Adelaide, South Australia, Australia, [b]CSIRO Land and Water, Black Mountain, Canberra, Australian Capital Territory, Australia, [c]Centre for Applied Water Science, University of Canberra, Canberra, Australia, [d]School of Life and Environmental Sciences, The University of Sydney, New South Wales, Australia
Email: tanya.doody@csiro.au

Abstract: Decline in river basin ecological condition continues to be a global trend due to anthropogenic overuse of water and the effects of climate change, particularly in arid and semi-arid basins. In the Murray-Darling Basin (MDB), Australia, the condition of riverine trees has been a concern across the Basin over the past 30 years. This is related to over extraction as well as saline groundwater impacts and long-term droughts. While water for the environment via environmental flows has been a keyway to alleviate ecological decline, we continue to grapple with how to robustly monitor vegetation condition across expansive basins such as the 1,000,000 km^2 of the MDB. Providing broadscale monitoring will assist decision making such as where to prioritize water for the environment to protect key ecological assets and preserve floodplain and riparian ecological function into the future. Over the past decade, significant investment has been made in evapotranspiration measurement of key riverine species *Eucalyptus camaldulensis* (River Red Gum) and *Eucalyptus largiflorens* (Black Box) in the southern MDB. Evapotranspiration provides an indicator of tree stand condition and has been quantified via plot-based measurements for both species, in both saline and non-saline environments. Transpiration in mm day^{-1} was measured using 10 sap flows sensors per plot. Measurement of soil evaporation and canopy interception was also undertaken. Plot scale measurements occurred for a minimum of 1 year and up to 4 years across 20 plots from 2008. Evapotranspiration rates varied greatly depending on frequency of flood inundation and magnitude of rainfall, with less flooding leading to lower rates of evapotranspiration and lower tree vigor. To scale evapotranspiration regionally, field data was compared to the outputs of CMRSET LandsatV2.1 timeseries. This can create a riverine tree remote sensing timeseries product to assist with broadscale tree monitoring and hence allocation and prioritization of water for the environment. To overcome mismatch between field and CMRSET evapotranspiration, a random forest model was trained using *in-situ* evapotranspiration and additional remote sensing products, to produce a model which accurately computes the *in-situ* riverine tree evapotranspiration irrespective of species and situation (i.e. whether severely drought stressed, situated over highly saline groundwater or with access to a permanent fresh water source). Using the random forest model, a monthly timeseries of evapotranspiration have been produced across the MDB for both *E. camaldulensis* and *E. largiflorens*, from 2012 to current time. Evapotranspiration thresholds based on field observations of canopy vigor were determined, to create a 3-class tree condition timeseries underpinned by the quantified evapotranspiration data. The tree condition timeseries provides visualization of riverine tree condition changes over the past decade for each 30 m pixel, allowing water managers to scrutinize the response of riverine tree in the MDB to drought as well as the application of water for the environment, informing decisions on where to prioritize limited resources.

Keywords: *Random forest model, transpiration, river red gum, water balance, environmental flow*

The effect of population model choice and network topologies on extinction time patterns

E. M. E. K. Ekanayake [a], **J. A. Webb** [a] **and M. J. Stewardson** [a]

[a] *Department of Infrastructure Engineering, The University of Melbourne, Parkville, 3010, Australia*
Email: emekanayake@student.unimelb.edu.au

Abstract: The inherently complex nature of riverine ecosystems limits opportunities to observe continual outcomes over longer time frames and across large scales. Therefore, we need to examine integrated effects of multiple small-scale observations on population processes at large spatial and temporal scales using ecological models. Thus, models of populations are a vital component for understanding and linking the processes and patterns of river networks across individuals, environments, ecological interactions, and population structures.

Population models of fauna used in river network studies vary based on parameters such as the number of species in the population (single or multiple), spatial explicitness or implicitness of migration, and the population's age structure. Population-based models consider the population as the base unit and assume all individuals to be identical in every way, while in stage-structured models individuals are grouped according to essential traits, with distinct population vital rates assigned to each group. Individual-based models consider all individuals separately, where each individual can potentially have different vital rates, and metapopulation models focus on occupancy of habitats rather than abundance. Therefore, inferences obtained through studies that have implemented different population models even within the same network might not be comparable.

This study aims to understand if different functional models in river systems produce significantly different model results (specifically for extinction patterns) and, therefore, whether conclusions are model-dependent. To assess the interaction between different population models and the topology of a river network, we used four network patterns. (1) Dendritic, (2) Linear, and (3) Trellis networks which are seen in river systems, and a (4) Ring lattice/Non-tree topology to provide a structure unlike those seen in river systems. The population models consisted of one patch-occupancy metapopulation model (M1) and three different individual-based logistic growth models (IBMs: M2-average vital rates assigned for all individuals, M3-age-structured, M4-explicit individual rates). The systems were simulated until they reached extinction, starting from fully occupied habitats. Results were obtained for the proportion of occupied patches at each simulation step and the extinction time of the entire network.

Dendritic, linear, and trellis structures did not show notable differences among extinction times for any of the four models. For M2 and M3, average extinction times decreased when the connectedness of the network increased, but this result was not seen for M4. The difference between topologies was higher for M1 compared to all three IBMs. Enhanced connectivity of the dendritic networks did not increase the extinction time over linear networks under M2 and M3, even in larger networks. We were able to observe a difference between IBMs and metapopulation models regarding the rates at which they reach extinction, and the size of the network affected population stability in the long run. However, there were no significant distinctions among the three IBMs, even though the rate of decline varied among topologies. Therefore, spatial arrangement and connectivity does not appear to be the sole predictor of single-species metapopulation responses if the occupancy data is obtained based on local subpopulations.

In conclusion, in terms of extinction and patch occupancy proportions, the outputs from functional models are robust to assumptions and varying levels of detail if they contain at least some detail at the level of individuals within habitat nodes. Also, if we are modeling network-scale populations, models that include at least some detailed information on individuals is a far better choice than considering populations implicitly. Finally, our results indicate that there is a minimum level of complexity that is required to achieve robust outcomes, but beyond this, further increases in complexity make little difference.

Keywords: *Dendritic networks, extinction time, occupancy patterns, individual-based models, metapopulation models*

Assessing waterbird breeding conditions using an emulator of wetland inundation regime

Juan Quijano[1], **Jose Rodriguez**[1], **George Kuczera**[1], **Patricia M. Saco**[1], **Steven G. Sandi**[1], **Rebecca Carlier**[1], **Li Wen**[2] **and Kelsey McDonough**[1]

[1]*School of Engineering, The University of Newcastle, Callaghan, NSW, Australia*
[2]*Department of Planning, Industry and Environment, NSW, Australia*
juan.quijanobaron@uon.edu.au

Abstract: Wetlands are essential habitat for waterbirds because they serve as breeding and roosting areas. Waterbirds are useful indicators of wetland ecological health and are essential for the ecosystem function but have been under pressure due to climate and anthropogenic drivers. Colonial waterbird breeding has been found strongly correlated to flooding and inundation regime (flood duration and timing). In this study we applied the WATHNET5 model, a simulation model based on linear programming, to estimate bird breeding events by emulating wetland inundation regimes. The objective is to estimate the occurrence and frequency of colonial waterbird breeding conditions pre/post the construction of a dam on an Australian dryland wetland as an indicator of ecosystem health. We applied the methodology to the Macquarie Marshes from Warren weir Gauge to Carinda Gauge which include the Northern Macquarie Marshes (NMM). The NMM was represented as a network of reservoirs and arcs that emulate the hydrodynamics of the NMM system at a daily time step, which was based on a previously developed 2D hydrodynamic model. The river hydraulics of routing and transmission loss were calibrated with gauge records at two sites from 1986 to 2015 with a Nash Sutcliffe Efficiency of 0.71. The inundation regime was characterized by simulating the timing, duration and total spring flow arriving at the NMM. The minimum conditions necessary for breeding events were represented by the occasions when inundation exceeded or met minimum inundation regime thresholds. Our model showed that it predicted waterbird breeding conditions with 81% accuracy using data from nest count campaigns available from 1986 to 2015. Further simulations were carried out for the period from 1913 to 2019, and results indicated that that the frequency of breeding conditions has decreased and the average time between events has increased since the Burrendong dam was constructed. WATHNET5 proved to be a versatile tool to simulate bird breeding conditions and inundation regime, and this methodology can be extended to potentially inform the management of floods and high flow events within the catchment.

Keywords: *Waterbird breeding, inundation regime, environmental water, WATHNET5*

EXTENDED ABSTRACT ONLY

Simulations of dryland wetlands to assess availability of habitat services

Steven G. Sandi [a], **Patricia M. Saco**[a], **Jose F. Rodriguez**[a], **Kelsey McDonough**[a], **Juan Quijano-Baron**[a], **Li Wen**[b], **and Neil Saintilan**[c]

[a] *Centre for Water Security and Environmental Sustainability and School of Engineering, The University of Newcastle, Callaghan, Australia,* [b] *Science Division, NSW Department of Planning, Industry and Environment, Sydney, Australia,* [c] *Department of Environmental Sciences, Macquarie University, Sydney, Australia.*
Email: steven.sandirojas@newcastle.edu.au

Abstract: Wetlands in arid and semi-arid areas are ecosystems of ecological importance. Vegetation on such systems is dependent on periodical floods that input sediments, nutrients and that provide the necessary recharge to soil moisture for vegetation maintenance. In general, wetlands provide habitat services for a rich biodiversity, but during dry periods they are of major ecological importance as they serve as refuge for fauna. The capacity of these systems to continue providing habitat in the long term depends on availability of environmental water which is often in competition with other water uses such as human consumption and agriculture. In addition to water regulation that effectively changes the natural water regimes in these environments, increased frequency and severity of droughts, changes in rainfall patterns, and increased temperatures due to climate change are also factors that will impact habitat services. Strategic delivery of environmental water within the framework of water sharing-plans should integrate simulation tools that can help produce the best environmental outcomes and identify critical conditions during drought and decision making should also include the best available projections of climate change.

Here, we implement an eco-hydraulic model that combines flood simulations with vegetation water requirements (Sandi et al., 2020a) and we simulate wetlands vegetation dynamics during a period of 30 years (1991 to 2021) for an iconic wetland system located in the lowland floodplain on the Macquarie River: the Macquarie Marshes. In our methodology, we relate the status of the vegetation, determined from both surveys and remotely sensed data, with hydrodynamic flood simulations in order to quantify thresholds of water that drive vegetation deterioration and recovery (Sandi et al., 2019). Our modelling framework provides a spatial quantification of the status of woody and non-woody vegetation patches at a scale that does not compromise difficulty of implementation with detail (Sandi et al., 2019). We use our simulations of vegetation status to assess habitat services provision during the last 30 years. Our analysis allows for identifying critical habitat conditions within the site during recent drought and dry periods and the impact these have on the habitat services. Our results show that during extended drought periods, vegetation areas providing habitat services are reduced in 50%. Shorter dry periods, can lead to up to 35% reduction in habitat services. In both cases, our model indicates some capacity for vegetation recovery once floods are reinstated, however, increases in intensity and frequency of dry periods can significantly intensify the impacts of droughts and dry periods on habitat services.

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Keywords: *Floodplain wetlands, habitat services, drought, Macquarie Marshes*

Modelling water fluxes across the Soil-Plant-Atmosphere Continuum using FETCH3

M.R.F. Silva [a], **A. M. Matheny** [b], **V.R.N. Pauwels** [a], **D. Triadis** [c], **Justine E. Missik** [d], **G. Bohrer** [d] **and E. Daly** [a]

[a] *Department of Civil Engineering, Monash University, Melbourne, Victoria, AUS,* [b] *Jackson School of Geosciences, The University of Texas at Austin, Austin, Texas, USA,* [c] *Department of Mathematics and Statistics, La Trobe University, Bundoora, VIC, Australia,* [d] *Department of Civil, Environmental, and Geodetic Engineering, Ohio State University, Columbus, Ohio, USA.*
Email: marcela.defreitassilva@monash.edu

Abstract: Modelling the water transport along the soil-plant-atmosphere continuum is fundamental to estimate and predict plant transpiration. FETCH3 is a ready-to-use open-access model for the simulation of the temporal and vertical dynamics of water storage and fluxes across the soil-plant-atmosphere continuum, accounting for the vegetation response to environmental conditions and soil water availability. The model combines the water transport pathways to one vertical dimension, coupling the soil, roots, and stem and assuring the continuity of the water fluxes between these three compartments. Assuming that the water transport in plants occurs as in a porous medium, FETCH3 applies equations similar to the Richards equation to simulate water fluxes from the soil, through the roots and above-ground xylem to the atmosphere. This results in a system of three partial differential equations describing the transport of water through the plant system, with sinks and sources for the transfer of water between the soil and the roots and from the leaves to the atmosphere. The system of equations was solved numerically using a finite difference numerical scheme, implemented in Python 3.

The numerical scheme was tested against exact analytical solutions for steady-state and transient conditions using simplified but realistic model parametrizations. FETCH3 presented small errors when compared to the exact solutions, reaching a maximum error of approximately 0.2% with respect to the exact solution at the tree top of a 6 m high tree for a case in which transpiration is dependent on both time and elevation. For a steady-state scenario, considering a more complex formulation, the error approached 0.4% of the exact solution at the tree top. FETCH3 was used to simulate sap flux data from *Eucalyptus parramattensis* and *Angophora bakeri.* The performance of FETCH3 was compared to a similar model where the equations were solved using a finite element scheme. For this case, FETCH3 reached a R^2 of 0.74 and presented continuous water potential along the soil, roots, and stem, indicating an efficient coupling of the three domains. FETCH3 was also calibrated against sap flux observations from a *Eucalyptus globulus* plantation, providing a final evaluation of the model. FETCH3 results agreed with observations, showing that the model is able to model realistic scenarios. Therefore, the results demonstrated that FETCH3 can correctly and efficiently simulate above- and below-ground water transport.

Keywords: *Ecohydrology, tree hydrodynamic modelling, transpiration*

Investigations of environmental assessments in the Murrumbidgee River system using satellite imagery and floodplain hydraulic model

Gurmeet Singh [a], **Mark Powell** [a] **and Richa Neupane** [a]

[a] *WaterNSW, Sydney, NSW 2150, Australia*
Email: gurmeet.singh@waternsw.com.au

Abstract: The Murray–Darling Basin Plan sets sustainable diversion limits, which require how much water can be used in the basin, while leaving enough water to sustain natural ecosystems. In consultation with Basin governments, the Murray–Darling Basin Authority (MDBA) has developed an assessment framework, to assess how much water is being saved through the Sustainable Diversion Limit Adjustment Mechanism projects (SDLAM). The adjustment mechanism works in two parts. Supply projects, which include some constraint projects, aim to improve water infrastructure and river operating rules. There are also efficiency projects, which improve water delivery systems, including urban and on-farm infrastructure.

In this paper, we describe outcomes from the implementation of the comprehensive modelling framework for the Murrumbidgee catchment, to support SDLAM objectives set out by the NSW Government and MDBA. The modelling system leverages previous work undertaken by WaterNSW's Computer Aided River Management (CARM) project in the Murrumbidgee catchment. It is comprised of hydraulic models covering extensive floodplains, floodplain storages, 195 wetlands, effluent creek systems and detailed 1600 km river network including 19 weirs from the Blowering/Burrinjuck dams to Balranald upstream of the confluence with Murray.

WaterNSW in collaboration with DPIE has implemented the floodplain CARM hydraulic model for an initial environmental assessment of the river system using range of flow scenarios from 16 GL/d to 150 GL/d at Wagga Wagga. MIKE11 models were used in conjunction with eWater Source models, Sentinel satellite imagery and flood intelligence on historical floods to calibrate and validate the models for a range of environmental flows modelled at Wagga Wagga with releases from upstream dams and tributaries. The process involved running MIKE11 flood models for 26 flow scenarios and calibrating the inundation extents of wetlands by reviewing the commence to flow, floodplain breakouts and return flows, establishing the connectivity of the floodplain and response based on Sentinel Satellite imagery. It is akin to modelling the floodplains with a quasi-two-dimensional approach in conjunction with MIKE11 one dimensional models. In this approach, the floodplains are modelled as a network of extended cross-sections in the floodplain, river branches and spills with the rivers. The river branches represent the topographical depressions, and the spills correspond with the river embankments considering levees and river/road embankments that intersect the floodplain. The boundary conditions for Commence to Flow (CTF) for the wetlands were established initially, using eWater Source models. These were calibrated to six lumped wetland reaches along the Murrumbidgee River from Wagga Wagga to Hay including the hydraulics of wetland link structures. These were then transposed onto the Mike11 hydraulic models for Quasi-2D calibration and validation using Satellite imagery, and flood intelligence based on local knowledge and council flood studies. The CTF was further refined for this study and established based on simulated flood scenarios.

The finalised flood inundation extents derived from the quasi-two-dimensional modelling approach are being used for assessment of environment flow delivery options envisaged under the Murray-Darling Basin Plan, building upon the operational CARM modelling system in the Murrumbidgee valley.

Keywords: *SDLAM, CARM*

Soil moisture-vegetation variability on coevolving landforms in semi-arid ecosystems

A. Srivastava , **P. M. Saco** , **J. F. Rodriguez** , **N. Kumari** , **and O. Yetemen** [a,]

[a] *Centre for Water Security and Environmental Sustainability and School of Engineering, The University of Newcastle, Callaghan 2308, Australia*
[b]*Faculty of Science, University of Technology Sydney, Sydney, 2007, Australia*
[c] *Eurasia Institute of Earth Sciences, Istanbul Technical University, Maslak 34469, Istanbul, Turkey*
Email: Ankur.Srivastava@uon.edu.au

Abstract: Soil-vegetation-topography interactions play a central role in the hydrologic cycle, as well as in the ecological and biogeochemical functioning of a catchment, particularly in semi-arid areas, which constitute approximately 40% of the world's land surface. These interactions control numerous processes for terrestrial water resources e.g., evapotranspiration, streamflow regimes, and water-energy interactions. Several biosphere-atmosphere processes interact with each other and are affected by soil moisture and vegetation conditions in semi-arid ecosystems. In these ecosystems, a tight coupling between geomorphic processes and hydrological processes exists, which in turn shapes the landscape.

Vegetation development is mostly controlled by the amount and availability of soil moisture in space and time; therefore, soil moisture is an important determinant in vegetation development, particularly in water-limited environments. Further, the shape of the topography at the hillslope or basin scale also plays an important role in soil moisture and vegetation distribution. For example, the aspect variations driven by solar radiation also constitute a characteristic of the topography which affects the development of the vegetation type and density on opposing hillslopes. These aspect-driven vegetation differences are more profound in water-limited ecosystems, where vegetation growth is limited by soil moisture availability. The vegetation differences which arise via aspect differences can be seen in different parts of the world, such as in the United States, Australia, Chile, Italy, Spain, and Israel. Due to differences in soil moisture, vegetation differences are typically observed when comparing vegetation cover and type on opposing hillslopes. These findings illustrate the interdependence between topography, microclimate, soil, and vegetation, which ultimately leads to landscape coevolution.

The role of soil moisture and vegetation in shaping landforms and how these landforms respond to various soil (anisotropy, root zone depth, infiltration capacity, and porosity), climatic (solar radiation and precipitation), geographic (latitude), and geomorphic (hillslope diffusion and uplift rate) factors are the main objective of this work. In this study, the Channel-Hillslope Integrated Landscape Development (CHILD) landscape evolution model (LEM) coupled with the vegetation dynamics Bucket Grassland Model (BGM) are used to analyse the coevolution of semi-arid landform-vegetation ecosystems. The modeling approach is used to investigate the implications of various soil, climatic, geographic, and geomorphic factors on soil moisture and vegetation variability over landscapes with different characteristics. To examine the role of factors affecting soil moisture variability and vegetation variability, a set of comparative LEM simulations driven by spatially uniform and spatially varied solar radiation, and a range of uplift rates and hillslope diffusion are designed. Besides these, complexity index is used to differentiate and quantify these differently evolved landscapes based on overall relief and slope variability of domain.

The results show that the spatial soil moisture variability and vegetation variability are more sensitive to the changes in landform (hillslope diffusion and uplift rate) and climatic factors (solar radiation, precipitation variability) compared to other factors considered in this study. Slope-area, soil moisture-area, and vegetation-area relationships revealed that landscapes steepen as uplift increases and also that the difference in soil moisture variability and vegetation variability between north- and south-facing slopes become more pronounced at higher latitudes. Additionally, it is found that uplift, hillslope diffusion, latitude, and mean annual precipitation (MAP) contributed significantly to complexity indices developed for this study.

Keywords: *Soil moisture, hillslope diffusion, uplift rate, CHILD, vegetation*

Ecohydrologic modelling in Australia: an application of RHESSys to a Mountain Ash catchment

Clare Stephens[1], Lucy Marshall[2], Fiona Johnson[2], Larry Band[3,4], Martin G. De Kauwe[5], and Anna Ukkola[6,7]

[1]*Hawkesbury Institute for the Environment, Western Sydney University, Richmond, NSW, Australia*
[2]*Water Research Centre, School of Civil and Environmental Engineering, UNSW Sydney, NSW, Australia*
[3]*Department of Environmental Science, University of Virginia, Charlottesville, VA, USA*
[4]*Department of Engineering Systems and Environment, University of Virginia, Charlottesville, VA, USA*
[5]*School of Biological Sciences, University of Bristol, Bristol, BS8 1TQ, UK*
[6]*ARC Centre of Excellence for Climate Extremes, Sydney, NSW 2052, Australia*
[7]*Climate Change Research Centre, UNSW Sydney, NSW, Australia*
Email: c.stephens@westernsydney.edu.au

Abstract: Under global warming, landscape processes that govern hydrologic behavior are expected to change. This could lead to nonstationary runoff response in many catchments, with consequences for the skill of hydrologic models that underpin water management. One potential solution is to use more detailed models that simulate the landscape processes expected to drive nonstationarity. For example, catchment-scale ecohydrologic models can simulate changes in vegetation growth and function together with subsurface storage dynamics and lateral moisture transport. All these processes are known to be important for determining catchment response under a changing climate.

The Regional Hydro Ecological Simulation System (RHESSys) is a state-of-the-art ecohydrologic model that has been applied for a range of research applications predominately in the USA, but also in Europe and Asia. However, RHESSys has yet to be evaluated in Australia. One barrier is the high fraction of endemic vegetation here, and the effort required to obtain suitable parameters to represent species that may not have been modelled at this scale before.

Here, we developed and tested a RHESSys model of Walshes Creek catchment ($54km^2$), which drains directly to Upper Yarra Reservoir. It is within the Victorian Eucalyptus Regnans (Mountain Ash) forests, which have been well studied due to their ecological significance, high carbon storage capacity, influence on Melbourne's water quality, and value to the forestry industry. We parameterized the vegetation in one RHESSys model based on the available literature for Mountain Ash forests, or other species of eucalypt where necessary. We also included an understory layer, nominally based on the commonly observed shrub / small tree Pomaderris Aspera.

As we are interested in the wider applicability of RHESSys in Australia, we developed a second model where the vegetation was characterized by the default 'evergreen tree' with some adjustments based on the Community Land Model (CLM) parameters for broadleaf evergreen species. By comparing against this 'default' model, we could assess the value of the site-specific parameters for projecting water resource availability. We found that, while the models performed similarly under current climate, their water balance simulations diverged under climate change scenarios. This suggests that, while detailed ecohydrologic models like RHESSys can provide valuable insights into catchments under change, the vegetation response should be carefully parameterized so that ecohydrologic sensitivity is estimated appropriately. In this presentation, we will also share some of the hurdles and 'lessons learnt' associated with setting up a complex model in a new environment.

Keywords: *Ecohydrologic modelling, climate change, Australian vegetation, virtual catchment*

Runoff prediction based on spatial variability of ground cover in grazing land: A statistical approach

Jagriti Tiwari[a], **Bofu Yu**[a], **Bantigegne Fentie**[b] **and Robin Ellis**[c]

[a] *School of Engineering and Built Environment, Griffith University, Kessels Rd Nathan, Queensland, 4111, Australia*
[b] *Department of Environment and Science, Ecoscience Precinct, 41 Boggo Road Dutton Park, Queensland, 4102, Australia*
[c] *Department of Environment and Science, Bundaberg, Queensland, 4670, Australia*
Email: jagriti.tiwari@griffithuni.edu.au

Abstract: The ground cover level has a profound influence on altering surface hydrological processes in grazing land (Scanlan *et al.* 1996; Owens *et al.* 2003). Considering the degree of the spatial and temporal variation of ground cover in grazing land, it is desirable to use a simple and robust model to represent the spatial variation in cover to quantify its effect on runoff and soil loss. The purpose of the study was to test whether a 2-parameter beta distribution could be used to adequately characterize cover variation in space at the sub-catchment scale.

Twenty sub-catchments in the Burnett-Mary Region, Queensland, were randomly selected with the area varying from 35.8 to 231 km^2. Thirty raster layers of ground cover at 30m resolution were prepared for these 20 sub-catchments with the average cover for the 30 layers ranging from 24% to 91%. Three methods (visual goodness-of-fit assessment and Kolmogorov-Smirnov (K-S) test, the fractional area with cover ≤ 53%, and estimated runoff amount for a given rainfall amount for the area with cover ≤ 53%) were used to test the appropriateness of the beta distribution to characterize the cover variation in space.

The K-S test on 30 x 100 samples of ground cover showed that the hypothesis of beta distribution for ground cover could not be rejected at the 0.05 significance level for 97.5% of the cases. A comparison of the actual and beta distributions in terms of the fractional area with cover ≤ 53% showed that the discrepancy was no more than 8% for the 30 layers considered. A comparison in terms of the estimated runoff showed that results using the actual cover distribution and the beta distribution were highly correlated (R^2 ranging from 0.91 to 0.98; the Nash-Sutcliffe efficiency measure ranging from 0.88 to 0.99). The mean absolute error of estimated runoff ranged from 0.98 to 8.10 mm and the error relative to the mean was 4 to 16%.

The results indicated that the 2-parameter beta distribution can be adequately used to characterize the spatial variation in cover and to evaluate the effect of cover on runoff for these predominantly grazing catchments.

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Keywords: *Ground cover, empirical distribution, beta distribution, runoff*

Modelling Water for Rivers: A case study of Snowy Water in the River Murray, Australia

M.J. Alam[a*], M. Hardy[a] and A. Korn[a]

[a] *Murray Darling Basin Authority (MDBA), Canberra, Australia*
[*]*Email: Jahangir.Alam@mdba.gov.au*

Abstract: Water for Rivers was a joint government enterprise that aimed to restore some environmental flows to the Snowy and Murray rivers. Significant works have been undertaken in the Murray Darling Basin that recovered water through various measures such as water efficiency programs and water licence purchases for environmental use. The recovered water establishes the River Murray Increased Flows (RMIF) mechanism, which provides up to an additional 70 GL each year to be released to the River Murray for environmental purposes (NSW Government, 2017). The RMIF water is held in the Snowy Hydro scheme, a dual-purpose development for electricity generation and regulated water supply for irrigators in the river valleys. The basin plan development and subsequent business case proposals on sustainable diversion limits (SDL) adjustments mechanisms have given more control over the operation of the RMIF water. Under the RMIF callout provisions, the water can be accrued and set aside for use at a time that provides maximum environmental benefit. Each state (New South Wales, Victoria, and South Australia) can optionally build a callable reserve in the Snowy Scheme by crediting the RMIF entitlements in Hume Dam through substitution of existing resources on the Murray (NSW Government, 2017). This paper aims to demonstrate how the RMIF callout provisions have been implemented in the Source Murray Model. The model's results illustrate that the RMIF callout provisions improve the flexibility of the River Murray environmental water portfolio.

The eWater Source modelling platform represents the river system through a network of nodes and links. It also has the Resource Assessment facilities that allow water accounting and decision making for resource allocations and water releases. In addition, the Source platform allows for customized functionality via additional software components, or plugins. The MDBA has developed several plugins for the Source Murray Model. Of critical importance to the Source Murray Model is its monthly assessment. This is implemented as a plugin ("Monthly Assessment") which implements the distribution of the water between NSW, Victoria, and South Australia as per the Murray-Darling Basin Agreement. Within the model, there are state-level Resource Allocation Systems. Each of these is a standard (non-plugin) component of the model, taking its distributable resource from the customized Monthly Assessment. Several additional Resource Allocation Systems represent other aspects of the system, such as allocation trade. To represent the various components of the Snowy-Murray releases, a dedicated Resource Allocation System was set up to track the various volumes referred to in the Snowy Water Licence (2002). This study has updated this Resource Allocation System to reflect changes to the Snowy Water Licence in 2011, including amendments to drought reserve, dry inflow sequence volume reserve, 200 GL flexibility provision, and wet sequence protection for pre-release. Further changes simulate the RMIF Callout Provisions. Separate accounts have been created for new entitlements of New South Wales (NSW) and Victoria in the model for handling the transfer of RMIF water from the Snowy to the Murray River.

Modelling Snowy RMIF water is complex. The input of Snowy Water to the Murray model includes three input time series provided by Snowy Hydro Limited, which consists of the Murray release, spills, and dry inflow sequence volume. These inputs are then rebadged to different components of RMIF to ensure water rules are preserved in the model. The model was run for a historical period from 1895 to June 2020. The performance of the model has been measured against MDBA's benchmark runs for basin plan and SDL modelling undertaken in MDBA's old monthly time step model MSM. The potential impacts and benefits on water allocations, use and volume of water held for environmental purposes have been assessed.

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Keywords: *Snowy Water, River Murray, environmental water, hydrological modelling*

Real-time water resource management using optimization methods and multi-criteria analysis, "Lake Baikal – Irkutsk Reservoir" case study

Alexander Buber[a] and **Mikhail Bolgov[b]**

[a] *All-Russian Research Institute of Hydraulic Engineering and Land Reclamation named after A.N. Kostyakov, 44, B. Akademicheskaya Str., 127550 Moscow, Russia*
[b] *Water Problems Institute, Russian Academy of Sciences, 3, Gubkina Str., 119333 Moscow, Russia*
Email: buber49@yandex.ru

Abstract: In the second half of the twentieth century, a cascade of reservoirs was constructed along the Angara: Irkutskoe, Bratskoe, Ust-Ilimskoe and Boguchanskoe, which were intended for producing renewable hydroelectric energy, transportation through the Angara and Yenisei Rivers, and for avoiding floods. The upper reservoir (Irkutsk Dam) is used to regulate the level of Baikal Lake. Operations are carried out using dispatch schedules (DS), developed on the basis of long-term hydrological series of the observed inflow and statistical analysis methods. Changing climatic conditions are impacting the effectiveness of the schedules.

This research presents a multi-criteria analysis of the Irkutsk reservoir operating modes under different hydrological conditions, based on dispatch schedules and optimization methods. It includes mathematical methods, algorithms and computational technologies for the formation of reservoir operation modes, allowing one to consider the long-term interval hydrological inflow series observations and the water users' requirements priorities hierarchy.

In the proposed computing technology, a statistical forecast is carried out for several years (tens of years) for the last years of the historical inflow, which reflect the ongoing climatic changes, and on this series the optimization task of the releases formation is solved, starting from a given initial reservoir volume. The optimization task is obtained with a dimension of about 1000 variables, solved by special methods developed by the authors in a classical deeply nonlinear setting.

Different inflow series scenarios were carried out according to the current rules, and optimization for the modern requirements of water users. Multi-criteria analysis by statistical criteria showed that the operating DS does not provide control with normative reliability in recent years and in the low-water period, but the optimization approach does. The results indicate that it is necessary to 1) to develop DS on historical hydrological series over the past 20–30 years, and not on the entire series, which distorts the coordinates of the DS, 2) update DS every 10–15 years, 3) create tools that allow you to control in real time using an optimization approach, such as the mathematical model and algorithm developed in this study. To support this, the study also proposed methods for generating a long-term multi-year inflow forecast.

In practical work, 11-year series of recurrence forecast were used, based on 11-year cycles of solar activity by Schwabe. An experimental proof of the correctness of the developed approach was carried out for an 11-year historical series from 1914 to 1924, according to DS, optimization along the entire series and optimization according to the proposed algorithm. The expected result was obtained: the security according to the proposed algorithm is higher than according to the DS (but naturally worse than when optimizing along the entire series). However, it is impossible to rigorously prove mathematically that the proposed algorithm gives better management than the DS for other reservoirs. Calculations were carried out using a program specially developed in the Visual Basic language with the Solver optimizer built into the Excel.

Keywords: *Dispatch schedule, inflow timeseries, Release rules, Optimization methods, Multi-criteria analysis, Trade-off analysis*

Converting stormwater drain into a series of wetlands for stormwater water quality improvement

Sandeep Choudhry[1], Darren Coughlan[2] and Ashok Sharma[1]

[1]Victoria University, Melbourne, Australia; [2]Greater Western Water, Melbourne, Australia
Email:[1]sandeep.chaudhry@live.vu.edu.au; [2]darren.coughlan@gww.gov.au; [1]ashok.sharma@vu.edu.au

Abstract: Urbanisation, population growth and climate change exert significant pressure on our waterways and environment. This often leads to an increased frequency of risk of habitat disturbance, erosion, and significant environmental damage. The level of contamination and pollutants in stormwater increase due to urbanisation resulting in further degrade the health of receiving waters. The most common stormwater treatment method which can be integrated to the urban design is the construction of wetlands. Wetlands are a suitable option for preventing such degradation and contribute to improving the stormwater quality by removing the pollutants, fine sediments, phosphorus and nitrogen, and can help achieve water quality objectives in an urban development.

These wetlands are vegetated systems, which are shallow and are drained in a controlled setting. The quality of vegetation, density & type are integral in enhancing the treatment performance. Wetlands are constructed in a series of treatment train such sediment ponds inlet zone and gross pollutant traps, these allow for protection of wetlands by eliminating coarse pollutants and sediments.

In this study, an earthen stormwater drain around 300m in length is planned to be upgraded into a series of wetlands to treatment stormwater at Greater Western Water's West Werribee site. The information collected for wetlands modelling and design is on stormwater channel catchment area; local topography; existing channel size/ length; past flow data for calibration and validation; soil properties; rainfall data for the area; soils characteristics; stormwater discharge point- disposal point and WSUD options for modelling. Interconnected three to four wetlands with associated structures along the channel length with different sizes will be modelled and designed for stormwater quality improvement.

eWater Model for Urban Stormwater Improvement Conceptualisation (MUSIC) for water sensitive urban design (https://ewater.org.au/products/music/) will be applied to model wetlands to achieve desired stormwater quality improvement objectives. The detailed design of wetlands will then be conducted using local WSUD design guidelines and available literature for wetlands and associated structures (Kadlec et al., 2006; Melbourne Water, 2020).

This research is the part of undergraduate civil engineering candidate's project at Victoria University with collaboration with Greater Western Water.

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***Keywords**: Stormwater quality improvement, MUSIC model, wetlands, WSUD*

An assessment framework for classifying determinants of household water consumption and their priorities for research and practice

A. Cominola[a,b], L. Preiss[c], M. Thyer[c,*], H. R. Maier[c], P. Prevos[d], R. Stewart[e,f] and A. Castelletti[g]

[a]Chair of Smart Water Networks, Technische Universität Berlin, Berlin, Germany
[b]Einstein Center Digital Future, Berlin, Germany
[c]School of Civil, Environmental and Mining Engineering, University of Adelaide
[d]Victoria University, Melbourne, Australia
[e]School of Engineering and Built Environment, Griffith University, Gold Coast, Australia
[f]Cities Research Institute, Griffith University, Gold Coast, Australia
[g]Department of Electronics, Information, and Bioengineering, Politecnico di Milano, Milan, Italy
Email: mark.thyer@adelaide.edu.au

Abstract: Achieving a thorough understanding of the determinants of household water consumption is crucial to support demand management strategies. Yet, existing research on household water consumption determinants is often limited to specific case studies, with findings that are difficult to generalize and not conclusive. Here, we contribute a framework for review, classification, and analysis of the literature on the determinants of household water consumption. Firstly, we identify a comprehensive set of 48 relevant publications, based on a systematic paper search. The framework firstly classifies household determinants into observable (physically seen/measured aspects of the house), latent (relates to the way occupants think/act/feel) and external (external to house and influence at regional level). Secondly, we undertake a trade-off analysis of different criteria that account for the representation of a potential water consumption determinant in the literature, its impact across heterogeneous case studies, and the effort required to collect information on it. The results of our trade-off analysis show that distinct groups of determinants exist, allowing for the formulation of four recommendation categories. These provide guidance for practitioners on which determinants to consider in practice and for researchers to prioritize in future research (Figure 1).

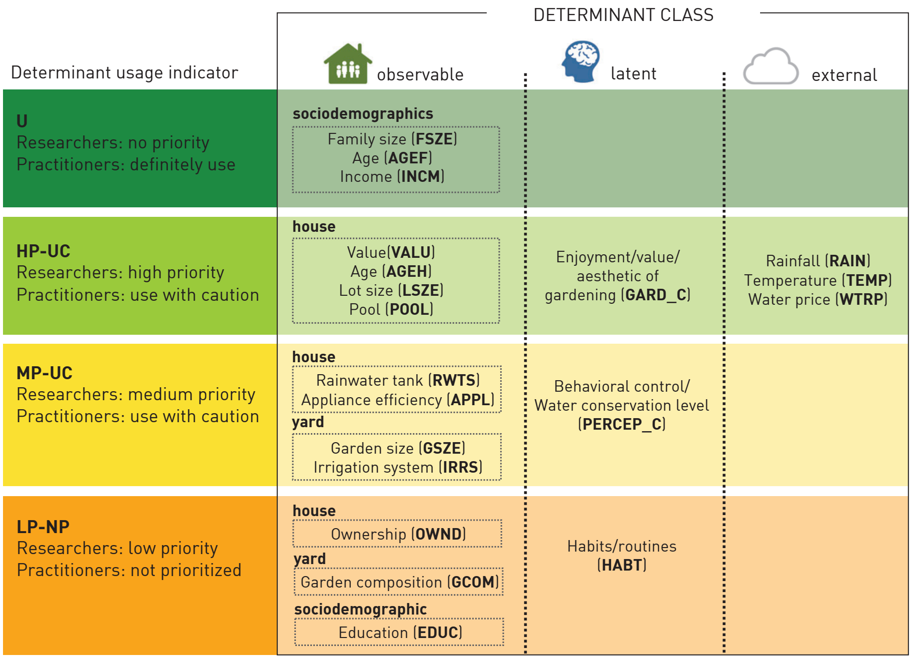

Figure 1. Recommendations for practitioners and researchers for individual determinants.

Keywords: *household water consumption, water consumption determinants, water demand management, smart meter, review*

Recent enhancements to the Source platform and future priorities

G. Davis [a], **Dr G Adams** [a,b] **and J. Moolman** [a]

[a] *eWater, Canberra,* [b] *Water Management Analysts, Canberra,*
Email: geoff.davis@ewater.org.au

Abstract: eWater is the custodian for Source, the Australian National Hydrological Modelling Platform. Source is a generalized model with catchment, water system planning, operations and forecasting modes. It can be used for all aspects of water resource management (Welsh et.al. 2130), including:

- water balance studies from catchment to river basin scale
- analysis of supply and demand balances, including agricultural, hydropower, urban, industrial and environmental demands
- water quality analysis
- reservoir and river operations, encompassing low to high flow events, water quality and system optimisation
- urban water system planning, operations and optimisation, including analysis of different supply and demand management options (reservoir/recycling/desalination/storm water)
- groundwater-surface interactions.

Every six months (June and December) eWater releases a new production version of Source, making available new or enhanced functionality, bug fixes and maintenance updates available to licensed Source users. This presentation will showcase the most significant enhancements to Source made since December 2020 (Source 5.4 and Source 5.10); including to calibration, scenario input sets, river operations, hot-start capability, increased distribution loss options, a new order analysis tool and new order recorders (eWater 2021). The latest release also includes improvements to MUSICX and Urban Developer, both of which are now available in Source.

Water management is always evolving, in turn eWater and its partners are constantly working to ensure the Source platform provides the functionality water managers require. Looking to the future, priorities for the coming years include improved capability to model land use change, including the impacts of bushfires, extending functionality in MUSICX, climate change analysis, representation of low-flows and transitioning to the Microsoft .net core framework.

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eWater 2021, Source User Guide 5.10, ISBN: 978-1-921543-80-7, eWater Ltd, Canberra.

Keywords: *Source, eWater, Urban Developer, MUSICX, land use change, climate change*

Water resource assessment in Afghanistan using eWater Source hydrological model

Fazlul Karim [a], **David J. Penton** [a], **Santosh Aryal** [a] and **Shahriar Wahid** [a]

[a] *CSIRO Land and Water, Canberra, ACT 2601, Australia*
Email: fazlul.karim@csiro.au

Abstract: Afghanistan is a mostly semi-arid country that depends on rainfall and irrigation using runoff from mountain snowmelt and groundwater, to produce food for its population. Afghanistan's water resources face pressure to support its growing population and continued economic development while the warming climate continues to deplete its glaciers (rivers from Afghanistan flow into six downstream countries). Managing the growing water demand under changing supply is a huge challenge that will require strategies and policies informed by science. To assess current and future water availability and to manage its water, the erstwhile National Water Affairs Regulation Authority (NWARA) of Afghanistan and CSIRO are jointly developing the Afghanistan National Water Information System (ANWIS). Hydrological models are the key to understanding the availability of surface water resources and identify effective water allocation schemes. We have reconfigured and calibrated regional hydrological models for the five major river basins of Afghanistan (Helmand, Harirod-Murghab, Kabul, Northern and Panj Amu). We have used a combination of GR4J and GR4JSG hydrological models to simulate catchent runoff. These models were initially configured by the eWater Ltd for training the Afghan government staff and were handed over to NWARA in 2019. We thank NWARA for sharing hydrological data and eWater Source model for the ANWIS project.

The area of the river basins varies from 71,995 km^2 (Northern Basin) to 327,660 km^2 (Helmand Basin). For hydrological modelling, each river basin was divided into multiple sub-catchments totalling 207. Each sub-catchment was divided into multiple functional units (FUs). Subcatchment boundaries were defined according to the major tributary confluences, historical gauge sites and the location of major dams. Since precipitation generally occurs as snowfall over the higher elevations and melting snow and glaciers are significant contributors to streamflow, FUs were derived using elevation bands at 500 m intervals to facilitate snowmelt modelling. The current model setup uses input data from 122 streamflow gauging stations, 19 weather stations and 28 snow sampling stations. Daily time series of observed flow and precipitation data for the period of 2008 to 2020 were obtained from NWARA. Precipitation data were gap-filled and interpolated to sub-catchments using the inverse distance weighted technique.

Parameters were calibrated using the daily Nash Sutcliffe Efficiency (NSE) and a bias penalty as the objective function and shuffled complex evolution as the optimisation function. For each river basin, model parameters were calibrated for two to three headwater catchments by comparing observed and simulated flow hydrographs. Calibrated parameters from the best performing catchment were transferred to other catchments in that river basin. During the calibration process, snow parameters such as melting temperature threshold, snow bucket, initial snow bucket and snow area were investigated and adjusted where necessary. Fig. 1 shows a typical comparison of observed and modelled discharge at a headwater catchment in the Harirod-Murghab River Basin. While an overall match was obtained between observed and simulated flow hydrographs (bias <10%), there were large differences for peak flows. For the calibration condition, daily NSE varies between 0.4 to 0.6 and the absolute bias varies from 5 to 20% among the five river basins. One of the main reasons for poor performance in peak flows is the uncertainty in observed flow. In many instances, we noticed inconsistencies between precipitation and streamflow. We are currently investigating these issues to improve the calibration.

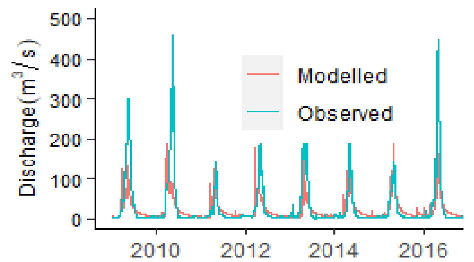

Fig. 1 Comparison of discharge at Chekhcheran

The eWater Source river system framework was used which makes it possible to explore water availability across multiple scales, from catchment to major river basins. Once calibration is completed, the models will be used to simulate water availability at ungauged catchments.

Keywords: *Water balance, GR4J, GR4JSG, model calibration, Functional unit*

Victoria's journey to adoption of Source

Uttam Manandhar [a], Michael Finger [a], Yong Li [a] and Seker Mariyapillai [a]

[a] *Department of Environment, Land, Water and Planning, Victoria, Australia*
Email: Uttam.Manandhar@delwp.vic.gov.au

Abstract: Source is an integrated modelling platform capable of simulating water systems, including both physical systems and the operational rules applied to them through policy, regulation, and management plans. It is developed using modern technology, with consistency and transparency in modelling, initially across the Murray-Darling Basin and later across Australia, as one of the key aims. Victoria has contributed significant technical support and funding to the development of Source since its initiation in 2008.

In Victoria, REALM (**RE**source **AL**location **M**odel - https://www.water.vic.gov.au/water-reporting/surface-water-modelling/resource-allocation-model-realm) has been the main hydrological modelling platform for more than 20 years. The Department of Environment, Land, Water and Planning (DELWP) has developed a strategy to guide Victoria's transition from the current REALM modelling platform to the Source platform (https://www.water.vic.gov.au/water-reporting/surface-water-modelling/source-transition). The strategy includes four main elements for completing transition to Source in Victoria, namely (i) Model development, completion, integration, enhancement and maintenance; (ii) Enhancing implementation systems and processes; (iii) Capability building and communication; and (iv) Monitoring, evaluation and reporting.

Victoria has progressed well and is on schedule for the development of Source models. The approach to development of Source models in Victoria has been to develop a foundational version model as a starting point for developing a reference version as a base case, and then develop further model versions to meet various core needs (e.g., current conditions model, compliance model etc.). Stages of reference versions and number of further versions of a model depend on system complexity and modelling needs in the system.

Various agencies have developed Source models across the state to meet their requirements, with base models completed for most of the larger systems and continuous improvements made as required. The status of Source model development can be categorised as **(A) DELWP base models**: 1) Complete with ongoing enhancement, 2) In development, 3) Not yet commenced; **(B) Other agencies base models**: 1) Complete with ongoing enhancement, 2) In development, 3) Not yet commenced; and **(C) No current requirement**. The completed base models with ongoing enhancement, i.e. Categories A1 and B1 cover ~89% and ~7% of storage volume capacities (including small catchment dams) in the state respectively, and the rest account for ~4%.

Victoria has progressed in the development of its Model Management System (MMS) by initiating system conceptualisation, exploring options available and consulting with different parties. The MMS aims to improve model accessibility for stakeholders and streamline the model development and application process by establishing a record of model version, improving collaboration, avoiding duplication and building capability.

In mid-2019, Victoria also established the Victorian Hydrological Modelling Group (VHMG) with involvement of a diverse range of professionals. It has been actively and regularly meeting since then and is the main stakeholder forum to collaborate on efficient and effective water resource modelling (WRM), including the transition from REALM to Source. Software issues, model sharing arrangements, and other matters related to WRM are also discussed, with the aim of supporting WRM capacity and capability building.

In 2020, Victoria prepared the performance framework for adoption of Source and model custodianship to guide monitoring and evaluation activities and completed the first evaluation. The performance framework set out an approach to evaluation, focussing on the measures of success that are of relevance to the adoption of Source. The evaluation was largely qualitative and informed primarily by stakeholder consultation. Key findings from the evaluation are (i) Source model development is progressing on schedule; (ii) DELWP continues to provide guidance and support for the adoption of Source; and (iii) Stakeholders indicated that, as a consistent and modern hydrologic modelling platform, Source supports a range of benefits for water resource management, including, ultimately, increased confidence and trust in the water management framework.

Adoption of Source requires state and national agencies to work collaboratively on model development as well as ensuring Source is continuously maintained and enhanced to meet stakeholders' on-going needs.

Keywords: *REALM, Source, transition strategy, hydrological modelling, water resource management*

Barwon Darling and Lower Darling Source model development for the Western Weirs Project and beyond

Hemantha Perera, Gurmeet Singh and Tahir Hameed

WaterNSW, 1PSQ, Level 14, 169 Macquarie St., Parramatta, NSW 2150
Email: hemantha.perera@waterNSW.com.au

Abstract: The Western Weirs Program study area covers a large number of permanent weirs between Mungindi in the Northeast on the NSW-Queensland border through to Menindee Lakes in the far west and down to the surcharge level of the Wentworth weir pool in the Southwest of the State. Two separate peer reviewed Source models were developed for the Barwon-Darling unregulated river, including a system link to the Lower Darling Source regulated river model to assess town water security and secure yield, assess the potential to improve flows and adaptive management, and provide outputs for environmental water requirements analysis and inform the economic cost-benefit analysis.

The Barwon Darling (BD) model represents 1600 km of unregulated river system from Mungindi to Wilcannia by configuring 20 weirs, 47 irrigation users, 11 Town Water Supplies (TWS) and 2020 Water Resource Plan rules. The model has 20 tributary inflows from Border, Gwydir, Moonie, Namoi, Macquarie, Condamine–Balonne, Warrego, Paroo valleys, and residual inflows for 13 river reaches. Robust calibrations for low, near median, and high flow regimes are achieved whilst accounting for consumptive diversions. An innovative method is demonstrated to simulate considerable flow losses along BD after a long dry period relative to similar events under normal flow conditions. The 2018 and 2019 environmental flow releases from the Border River dams provided a good opportunity to verify model performance with recorded flows, when no irrigation diversions were permitted.

The Lower Darling (LD) model is developed separately with inflows from Wilcannia and Talyawalka from BD model and extended to Wentworth representing the regulated system. It incorporates 37 rainfall runoff models, Menindee Lakes operational and harmony rules, resource assessment, environmental water requirements and the Murray water sharing rules. This model also incorporates floodplain storages and anabranch lakes that were configured with inputs from hydraulic model developed for the LD. The modelled low to near median flows at key gauges on the Lower Darling River, and consumptive diversions and environmental releases for the calibration period matched well with the recorded flows.

The model simulated data for 119 years determined that the TWS weirs at Mungindi, Brewarrina and Weir 32 are sufficient, and the Collarenebri, Bourke, Louth, Tilpa, and Pooncarie weirs need to be increased to meet projected TWS demands. The Wilcannia and Walgett weirs improve water security with current weir raising projects. The Angledool, Goodooga and Gongolgon weirs on BD tributaries are unable to meet the demands. Alternative options to increasing the capacity of weirs through augmentation of flows from upstream regulated river systems to meet shortfalls during droughts are explored in the paper.

Knowledge and experience from the comprehensive Source models linked to hydraulic models would be used in future to explore several augmentation options for the Menindee lakes as part of the Sustainable Diversions Adjustment Mechanism projects.

Keywords: *Barwon Darling, eWater Source, Western Weirs*

Source: a water resource modelling system for supply augmentation planning

Ashok K. Raut, **Richa Neupane, Golam Kibria and Mahes S. Maheswaran**

WaterNSW, Parramatta, Sydney, Australia
Email: Ashok.Raut@WaterNSW.com.au

Abstract: Water sharing and management plans and policies in Australia have long been supported by the analytical capabilities of water balance simulation models. The ability of these models to assess the likely outcomes of various policy scenarios inform stakeholders to decide on acceptable or optimal settings. WaterNSW has recently developed water resources planning models for all regulated basins in NSW including the Border Rivers Basin, where WaterNSW has responsibility of bulk water supply.

The Border Rivers is a complex water resource system with several major rivers and tributaries and head storages. The resource is shared between two states – NSW and Queensland. The current supply reliability of the system has been less than 50% and this is worse in the recent drought years. In 2019, NSW and Federal government jointly announced a proposal of Critical State Significant Infrastructure (CSSI) program that include three dams in the Northern NSW valleys including a new dam on the Mole River. This paper aims to demonstrate the application of SOURCE to evaluate the NSW's decision of constructing a new storage on one of the major unregulated tributaries such as the Mole River Dam as a supply augmentation option.

A calibrated daily baseline SOURCE model has been developed for the Border Rivers Basin and the Mole River Dam has been configured with the necessary changes in the resource assessment of NSW that is expected to have its 100% ownership. The model is run from 1911 to 2016 to calculate the relevant modelling outputs such as regulated release, effective allocation, and so on for various Mole River Dam storage sizes such as 50, 100, 150, and 200 GL. These modelling outputs can be converted into economic terms to calculate the project benefits. These benefits can be compared with the project costs to calculate the return on the investment. It is thus clear that SOURCE can be used as a water resource modelling system tool for supply augmentation planning.

Keywords: *Border Rivers, SOURCE, Mole River, Macintyre, Dumerisq*

Integrated modelling approach for sustainable water supply and demand planning

M. Sapkota [a], **A. Dey** [a], **J. Moolman** [a], **J. Wang** [a], **C. McTaggart** [b], **and J. Lee** [b]

[a] *eWater Ltd., Bruce, Australian Capital Territory, 2617, Australia*
[b] *Barwon Water, Geelong, Victoria, 3220, Australia*
Email: mukta.sapkota@ewater.org.au

Abstract: Growing population and climate change are putting increased pressure on water resources. Integration of centralised and decentralised water supply options along with demand management can offer a robust solution. Such integration requires an integrated modelling approach which can consider the interaction between these systems, and can adequately consider climate change, water restriction and water conservation. However, most water resources planning models currently available are mainly focused on centralised bulk water supply system. Approaches for estimating urban demands are typically based on interpolation of population growth and historical water consumption records. There are some models that consider the impact of demand management and alternative water supplies, but without any explicit representation of the key factors, such as climate change and the use of water conservation measures. Usually, those models are based on very generic excel based demand database which are not integrated with water supply system. Therefore, there is a need of direct integration between demand and supply models for long term sustainable water management. Further to that, these demand models should be able to assess the impact of end-use analysis, climatic variables, alternative water supplies, population growth, change in occupancy probability, varying water use appliances and water restrictions (Sarkar and Gato-Tirnidad, 2017). Urban water supply management requires supply models of water systems representing water demands and changing demands using an approach consistent with the current understanding of the contributing factors.

eWater, in consultation with its government owners and project partners, has developed an integrated modelling tool to address the above needs using the eWater Source modelling platform and the Urban Developer model. Source is an integrated hydrological model applicable for water planning, management, and operation. The Urban Developer model can assess multiple water service provision options and determine the urban water demand. Urban Developer can also simulate probabilistic end-user demand. The use of this integrated platform will assist in better informing future water planning decisions and aid urban water managers working towards integrated and sustainable water management.

The applicability of the integrated model has been demonstrated by updating existing demand models for Geelong, Victoria. Urban demands for the study area are generated using the Urban Developer model within the Source modelling platform. Replacing the existing hardcoded time series approach with an urban behavioural demand model offers the flexibility required for predictive demand modelling. The model provides a basis for historical and future urban demand modelling according to an increase in end-use demands based on population growth and climate change. The Urban Developer demand model allows representation of urban water demand and changes in these demands by incorporating alternative water supply options and specific appliance uses. These demand models provide long term future demands according to a range of future scenarios for population growth, changes in appliance efficiencies, population seasonality and future climate uncertainty.

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Keywords: *Integrated urban water modelling, Source, urban developer, sustainable water planning*

Impact of climate change and dynamic vegetation and soil conditions on water resources in a sub-tropical catchment in South-East Queensland, Australia

Chao Deng[a], **Hong Zhang**[a], **and David P. Hamilton**[b]

[a]*School of Engineering and Built Environment, Griffith University, QLD 4222, Australia*
[b]*Australian Rivers Institute, Griffith University, QLD 4111, Australia*
E-mail: chao.deng@griffithuni.edu.au

Abstract: The impact of anthropogenic climate change and land cover change on hydrological processes has been studied globally, but few studies have included non-stationary effects from changes in vegetation cover and soil properties. These changes could influence the future availability and quality of water at a catchment scale. The objective of this study was to assess how climate change impacts extreme flows and water security under different climate change scenarios (Representative Concentration Pathways (RCPs) 4.5 and 8.5). We used the Soil Water Assessment Tool (SWAT) model to simulate the hydrologic processes for the Upper Nerang River catchment located in South-East Queensland, Australia. Projected changes in vegetation cover and soil properties were done using models that relate leaf area index (LAI) (Tesemma et al. 2014) and soil organic carbon (SOC) (Sierra et al. 2014) to climatic variables, respectively.

The SWAT model was calibrated and verified against observations of streamflow, and sediment and nutrient loads from the Water Monitoring Information Portal of City of Gold Coast and from SEQwater for 2008 – 2015 and 2016 – 2019, respectively. We applied the perturbation factors to the climate time series data baseline of 1985 – 2014 for two future periods of 2040 – 2069 and 2070 – 2099 under two emission scenarios (RCP4.5 and RCP8.5). LAI was projected to decrease by 0.4% to 16.9% for pasture and from 0.4% to 10.6% for forest, respectively, due to the projected lower soil moisture under future climate conditions. SOC in topsoil was estimated to decrease by 6.2% to 11.6% for pasture and from 5.9% to 10.5% for forest under future changes in vegetation cover. The SWAT model was run using climate change (CC) scenarios, and using combined conditions of climate change, vegetation and soil dynamics (CC-LS) for the abovementioned future periods and scenarios. Streamflow showed greater variability and higher magnitude of extreme peak flow with higher return periods for 2040-2069 than for 2070-2099 while baseflow decreased under all future climate scenarios compared to the baseline. More streamflow was predicted for CC-LS scenarios (-9.3% to 7.2%) than CC scenarios (-11.2% to 5.0%) while both CC and CC-LS scenarios had less streamflow under the RCP8.5 scenarios (-3.5% to -11.2%). Loads of sediment (-4.7 to -28.4%) and total nitrogen (-5.9% to -26.2%) were predicted to decrease under RCP8.5 for both CC and CC-LS scenarios. Total phosphorus (TP) loads were predicted to decrease (-1.3% to -21.3%) under all future scenarios and conditions. The CC-LS scenario showed more streamflow but lower sediment and nutrient than the CC scenarios for each period and RCP case. The findings of this study indicate that non-stationary features of climate-induced change in vegetation cover and soil carbon should be taken into consideration for modelling catchment hydrological changes and water yields in future climate change scenarios.

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Keywords: *Climate change, leaf area index (LAI), soil organic carbon (SOC), water resource, SWAT*

Streamlining access to Bureau of Meteorology's Water Data

Andrew C. Freebairn [a], **J-M. Perraud** [a], **D. Penton** [a] **and J. Lerat**[a]

[a] *CSIRO Land & Water, Canberra, Australian Capital Territory*
Email: andrew.freebairn@csiro.au

Abstract: The Bureau of Meteorology (BoM) has been collecting, interpreting and disseminating Australia's water information since the inception of the Water Act in 2007. BoM is sharing the data with the public through the `Water Data Online' web application that allows browsing and downloading standardised data. The data is also accessible via a web data service which is publicly available. However, building data queries for this service remains a complex task which requires intimate knowledge of the Sensor Observation Service version 2 protocol (SOS2) which underlies Water Data Online products. SOS defines a Web service interface which allows querying observations, sensor metadata, as well as representations of observed features (https://www.ogc.org/standards/sos). The SOS queries take the form of extensible markup language (XML) that are software and hardware independent.

Client bindings provide a language specific interface to the web service. They are common in the software world – especially through the OpenApi/Swagger family of standards and products for RESTful web services. Client bindings typically handle conformance to language-specific conventions, conversion of datatypes from those defined by the web service to those native to the language, and handling of web communication including appropriate error handling and caching. Since the Bureau do not provide client bindings for their SOS service, the community of users are responsible for developing and maintaining these libraries. Two libraries have emerged: the sos4py - a generic SOS service binding for Python, and bomWater – a specific implementation for the R language. In this paper, we introduce a third – pybomwater, which aims to simplify the task of consuming the Bureau's services. Our client bindings (pybomwater) adhere to the Open Geospatial Consortium (OGC) Sensor Observation Service (SOS version 2) standard, with the aim to reduce the complexity in obtaining data supporting hydrological modelling.

Our bindings reflect the four SOS endpoints provided by the BoM services.

- GetCapabilities - lists available operations (GetCapabilities, GetFeatureOfInterest, GetDataAvailability and GetObservation), filter capabilities (spatial and temporal), a list of observable properties (e.g. Water Course Discharge), and offerings (e.g. Timeseries type DMQaQc.Merged.HourlyMean.HR),
- GetFeatureOfInterest – lists geographic features or locations by identifiers, filtered by timeseries types, area point location or parameter type
- GetDataAvailability – lists procedure (e.g. DMQaQc.Merged.DailyMean.24HR), properties (e.g. Ground Water Level), feature of interest (e.g. Cowra-Back Ck Nth P2) and phenomenon (e.g. time period)
- GetObservation. – returns the observation values filtered by the feature of interest, property, parameter and time period.

The pybomwater package can be installed from PyPi (python published packages) with 'pip install bomwater', the code can be obtained from Github at 'https://github.com/csiro-hydroinformatics/pybomwater' and a Jupyter notebook demonstrating the package usages is available at 'https://github.com/csiro-hydroinformatics/bomwater-notebook'.

Keywords: *Data accessibility, Sensor Observation Service, Python*

Sewer pipe tree root choke prediction using AWRA-L

A.J. Frost[a], A. Shokri[a], A. Azarnivand[a], G. Keir[a], M. S. Yee[b] and L. Uthayakumaran[b]

[a] *Australian Bureau of Meteorology, Australia*
[b] *Sydney Water, Australia*
Email: andrew.frost@bom.gov.au

Abstract: Sydney Water provides services in water supply, wastewater, recycled water and some stormwater applications to more than five million people in Sydney, the Illawarra and the Blue Mountains. As part of that role, Sydney Water owns and maintains a vast pipe network infrastructure to supply these services. Sewer network chokes (blockages) are a costly problem, in terms of reactive maintenance but also in terms of potential impact to the environment and our community, Sydney Water's reputation and associated regulatory action administered by the NSW Environmental Protection Agency (EPA) for sewer overflow incidents. With approximately 15,000 chokes per year and an average of 100 EPA notifiable incidents per month, this is a significant economic and reputational issue for Sydney Water. Identification of areas with increased risk of chokes, in particular root chokes (caused by intrusion of tree roots) is a priority within the organisation.

Previous investigation has shown that the number of root chokes per year is highly correlated with modelled deep soil moisture generated from the Bureau of Meteorology's Australian Water Resource Assessment Landscape model (AWRA-L) across Sydney Water's operational area. This is due to tree root intrusion into the sewer network during extended dry periods, as the tree roots seek water and nutrients within the sewer. The Bureau of Meteorology has recently expanded the capability of services relating to AWRA-L to now produce seasonal forecasts. The relationship between soil moisture and chokes and the availability of the soil moisture forecasts enables exploration of tools that can support prediction of areas having higher root choke risk.

This work describes development of an experimental root choke prediction model (trialling logistic regression and random forest machine learning approaches) based on seasonal predictions of soil moisture and other variables from AWRA-L. The root choke prediction model uses historical and seasonal forecast outputs of AWRA-L (available through the Australian Water Outlook service www.bom.gov.au/water/awo), along with characteristics of the sewer network and environment, to predict a likelihood of failure for any sewer in the network in any month. Automated and subjective methods were trialled for selection of thresholds for determining pipes as high risk. Pipe-based risks were aggregated to provide regional estimates of failure risk. The key outcome of the work was pipe failure risk forecasts over Sydney Water's area of operations for July-September 2021 based on seasonal forecasts, successfully demonstrating the approach. Further, the models applied supply insights into which factors influence pipe choke risk. See Frost et al (2021) for further details.

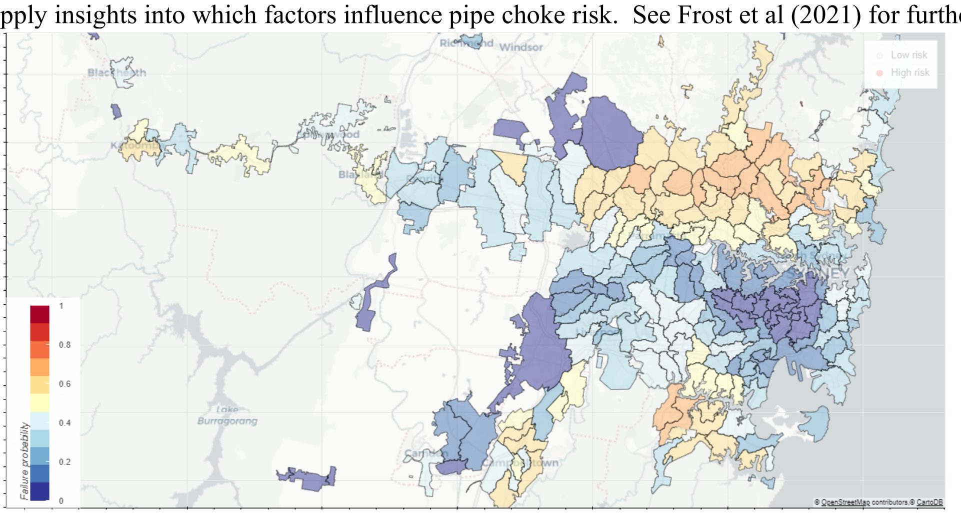

Figure 1. June 2021 Forecast risk of pipe failure for September 2021 over the Sydney region (0.53 failure threshold). Warmer colours show reagions with higher risk of failure.

REFERENCE

Frost, A., Shokri, A., Azarnivand, A., Keir, G., 2021. Spatial root choke prediction modelling for Sydney Water: Technical report describing methodology and results. Bureau Research Report – BRR058.

Keywords: *Spatial prediction, pipe tree-root chokes, random forest model, soil moisture*

EXTENDED ABSTRACT ONLY

Recent improvements to the Australian Water Resources Assessment Landscape Model (version 7)

A.J. Frost, A. Shokri, G. Keir, K. Bahramian and A.Azarnivand

Bureau of Meteorology, Australia
Email: andrew.frost@bom.gov.au

Abstract: We present improvements to the Australian Bureau of Meteorology's operational hydrological model, the Australian Water Resources Assessment Landscape model (AWRA-L). AWRA-L is a continental, gridded, daily time-step, water balance model, developed over the last decade by CSIRO and the Bureau of Meteorology for historical monitoring and water resource applications. AWRA v7 has recently been released as part of the Australian Water Outlook service at www.bom.gov.au/water/awo.

AWRA-L v7 contains significant improvements across the water balance due to altered:

- inputs: updated static grids, dynamic climate inputs (eg. adding vapour pressure) and calibration data,
- conceptual structure: addition of an urban hydrological response unit, addition of baseflow ephemerality, and modifications of top-layer soil drainage for better dynamics, and
- calibration approach: using additional remotely datasets and a spatially distributed calibration procedure.

The spatial calibration uses remotely sensed Terrestrial Water Storage (TWS) from NASAs Gravity Recovery and Climate Experiment (GRACE), and MODIS-based estimates of fraction of vegetation in addition to streamflow, evapotranspiration (CMRSET) and soil moisture (ASCAT) over 300 catchments nationally. Further, TWS is weighted highly in the objective function at 50%, halving the existing streamflow weighting.

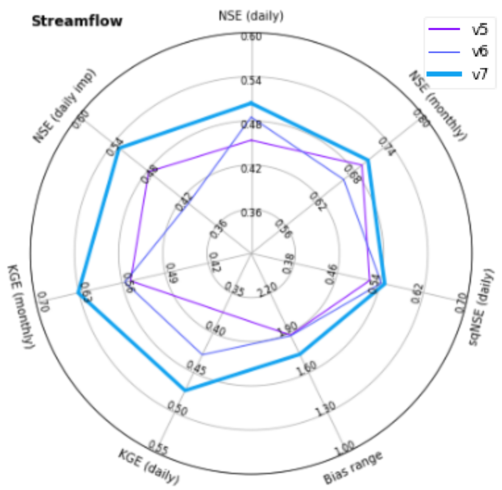

Figure 1. Performance of the AWRA-L v5, v6, and v7 for streamflow. Outer=better, KGE=Kling-Gupta efficiency, NSE= Nash-Sutcliffe efficiency

AWRA-L outperformed previous versions across the water balance based on comparisons with various national datasets reserved for validation including streamflow observations across 300 unimpaired catchments, flux tower observations from the OzFlux network, soil moisture (Murrumbidgee OzNet, Upper Hunter SASMAS, national OzFlux and CosmOz) networks, groundwater recharge observations and MODIS vegetation. The changes result in a significantly better streamflow performance nationally; bias across all catchments is significantly decreased (measured by bias range) due to ephemerality of streamflow being better reproduced and for urban catchments (see Fig. 1 for median performance metrics). Further, AWRA shows improved performance for soil moisture, groundwater, ET and vegetation. The improvement in streamflow is notable considering the altered approach to calibration focussing on the whole water balance, rather than predominantly streamflow. This improved performance against independent validation datasets gives confidence in the use of AWRA-L for water monitoring, water resource assessment, and other applications (see Frost et al. 2021a, 2021b for further details).

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Keywords: *Continental scale modelling, spatial calibration, water balance*

Use cases of the Australian Water Resources Assessment Model (AWRA-L v7)

A.J. Frost, **G. Kier, A. Shokri and A. Azarnivand**

[a] *Bureau of Meteorology, Australia*
Email: andrew.frost@bom.gov.au

Abstract: This work outlines three use cases of the Australian Water Resources Assessment Landscape model version 7 (AWRA-L v7), released in 2021 by the Bureau of Meteorology as part of the Australian Water Outlook suite (www.bom.gov.au/water/awo). The historical component of this service provides national daily 0.05° gridded AWRA-L outputs (from 1911 until yesterday), including runoff, soil moisture, evapotranspiration and deep drainage. AWRA-L v7 follows previous operational model versions (version 5 and version 6; released in 2015 and 2018 respectively) available to the public for near real time and historical modelled catchment conditions across Australia. This work details use of AWRA-L v7 historical data to demonstrate its value in three uses cases relating to drought, flood and fire risk estimation. Comparisons in performance compared to previous AWRA-L versions (v5 and v6) are also presented.

Drought: the ability of AWRA-L to reproduce observed shifts in the annual rainfall-runoff relationship during extended dry periods is investigated. We use 480 unimpaired catchment streamflow records to determine observed behaviour following the approach of Saft et al. (2015). This two-state behaviour (lower runoff for the same rainfall amount compared to predrought times) occurs over large parts of Southeastern Australia. Reproduction of this two-state behaviour is important in reproducing variability. We show that AWRA-L v7 reproduces the observed state behaviour over 67%/58% of catchments nationally/Victoria. This performance is challenging to achieve for catchment based rainfall-runoff models, let alone a national water balance model.

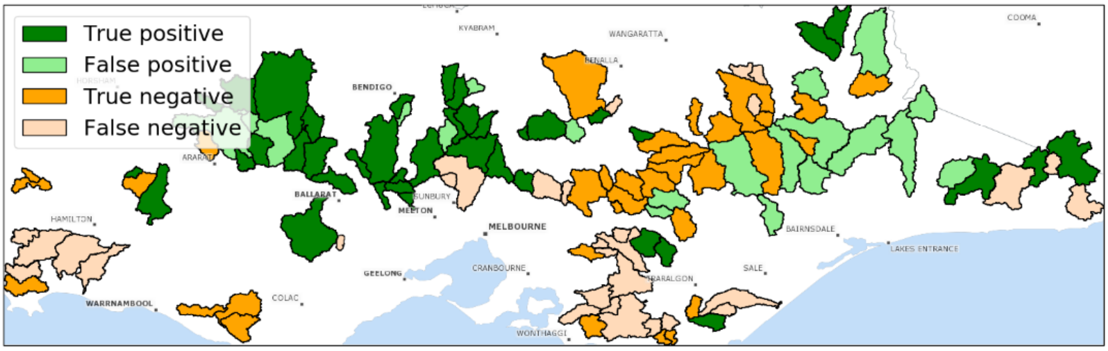

Figure 1. Reproduction of observed two-state runoff behaviour by AWRA-L v7 according to Saft et al (2015) analysis

Flood: AWRA-L is used to estimate initial loss parameters for the Bureau's operational event-based catchment flood model URBS; helping flood forecasters estimate antecedent soil conditions. This is achieved through correlating past event parameters to historical AWRA-L outputs; then using the relationships derived to estimate antecedent conditions based on near real-time AWRA-L outputs. Single site regression models of initial loss are improved with use of AWRA-L v7, compared to previous versions. Significantly, a multi-site multivariate model is developed opening possibilities for national initial loss map production for operations and also for design purposes.

Fire: we relate AWRA-L outputs to live fuel moisture content, towards near real-time fire risk estimation and forecasting. AWRA-L soil moisture is used in regression with live fuel moisture content and shows significant correlation, raising the possibility of use of these outputs for forecasting fuel content and fire risk. Additionally, use of vegetation directly from AWRA (rather than soil moisture) further improves the model. This indicates great potential for use in fire risk forecasting applications when using AWRA-L in forecast mode.

REFERENCE

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Keywords: *Water balance, risk, drought, flood, fire*

EXTENDED ABSTRACT ONLY

Downscaling remote sensing soil moisture assimilation models using data fusion and deep learning

Ignacio Fuentes[a], **José Padarian**[a] **and R. Willem Vervoort**[a]

[a] *School of Life and Environmental Sciences, The University of Sydney, New South Wales*
Email: ignacio.fuentes@sydney.edu.au

Abstract: Different soil moisture datasets have been developed which capture the spatio-temporal dynamic of water content in soils. However, most of these products have a low resolution and are mainly focused on estimating soil moisture at the soil surface. The aim of this work is to develop surface and subsurface soil water content maps at field scale (90 m resolution) by downscaling the Soil Moisture Active Passive (SMAP) North American Space Agency (NASA) - United States Department of Agriculture (USDA) datasets through data fusion and deep learning models. Additionally, by applying game theory to the machine learning process using SHapley Additive exPlanations (SHAP), the importance of the variables used in the downscaling can be analysed. As input data for the downscaling, the following datasets were used: Synthetic Aperture Radar data from Sentinel 1 satellites and relative surface soil moisture derived from it, soil clay content, soil organic carbon, and soil available water capacity at different depths from the Soil and Landscape Grid of Australia, 30 days lagged rainfall from the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS), 30 days lagged surface and subsurface soil moisture at 10 km resolution from the SMAP NASA-USDA dataset, surface reflectance and land surface temperature from the 8-days Moderate Resolution Imaging Spectroradiometer (MODIS) satellites, and land use/land cover information from the Australian Land Use and Management Classification and from the MCD12Q1 dataset. The downscaling used deep learning models consisting of dense layers and long short-term memory (LSTM) layers. These were trained and validated using soil moisture reference data from the Oznet and OzFlux networks. Results show a good performance of the downscaling for different land cover types, with average root mean squared errors, mean absolute errors, and Pearson correlations in surface of 0.07, 0.054 and 0.73, respectively. These results degrade slightly in depth to 0.068, 0.059, and 0.5. Interpretability shows that low resolution satellite derived soil moisture (SMAP) plays the strongest role in the deep learning models for surface soil water content, while soil properties increased in importance in depth.

Keywords: *Soil water content, downscaling, remote sensing, deep learning*

Treatment of uncertainty for root cause analysis of leakage alarms in open water channels for agricultural water delivery infrastructure

Samuel T. Hutchinson and **Joseph H.A. Guillaume**

Fenner School of Environment and Society, The Australian National University, Canberra, Australia
Email: samuel.hutchinson@anu.edu.au

Abstract: Operators of irrigation networks face increased demand to verify and improve network performance, including closing the water balance. Infrastructure automation initiatives not only bring performance improvements to the network, but also add value to capital investments through opportunity to analyse automation data. This research investigated the potential of actioning of leakage detection alarms to complement other network performance analysis tools and generate increased systematic understanding of the water balance gap.

Extending existing methodology in the literature for generating leakage alarms from telemetered infrastructure (Bedjaoui and Weyer, 2011), this study aimed to understand the impacts of uncertainty on how leakage can be detected and the follow-up process of leakage analysis, leading to three major contributions. Firstly, an approach is developed to filter uncertain alarms and clear false positives from leakage detection methodology using three key steps: threshold selection to maximise sensitivity in leakage detection, removal of uncertain alarms, and corroboration with other data sources to resolve the cause of the alarm. Secondly a modification is made to previous leak detection methodology to allow for data to be sampled at irregular intervals (as is commonplace in SCADA), along with quantification of the consequences of such data sampling on alarm uncertainty. Analysis of simulated leaks helped evaluate the limits of leak detection, and historical analyses of leakage alarms in a selection of pools throughout an irrigation season demonstrated how some key water balance exceptions can be diagnosed and followed up within the organisation. The final contribution is a discussion of the potential role of other datasets available to a network operator when performing root cause analysis and implications of value and cost of different information sources in embedding leak detection within operational and strategic organisational decision making.

In the context of expected measurement uncertainty and model simplifications, this research demonstrates a proof of concept for the potential of leak detection to not just be a source of operational alarms, but also become a central tool in helping to mobilise data science in the move towards learning-oriented data-driven irrigation organisations. The authors thank Murrumbidgee Irrigation for their collaboration and access to data from operational infrastructure for this project.

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Bedjaoui, N. and Weyer, E. (2011) ‘Algorithms for leak detection, estimation, isolation and localization in open water channels’, *Control Engineering Practice*, 19(6), pp. 564–573.

Keywords: *Leakage detection, SCADA, irrigation networks, root cause analysis, water balance closure*

Recent learnings towards achieving high quality probabilistic predictions in practical applications of hydrological models

Dmitri Kavetski, **David McInerney, Jason Hunter and Mark Thyer**

School of Civil, Environmental and Mining Engineering, University of Adelaide.
Email: dmitri.kavetski@adelaide.edu.au

Abstract: Hydrological predictions – and environmental predictions in general – are inevitably affected by substantial uncertainty due to limitations in data quality and model simplifications. Probabilistic predictions, where predictive uncertainty is represented using probability distributions, provide a vehicle for reflecting these uncertainties. Initially limited to research applications, probabilistic predictions are increasingly appealing in practical applications to help guide risk-based decision-making. For example, in water resource modelling, probabilistic predictions can provide reliable estimates of streamflow in the days and months ahead – thus avoiding a false sense of security in applications as diverse as dam operation, drought management, ecological health monitoring, and so forth. Nevertheless, a number of barriers still exist that impede a wider adoption of probabilistic predictions in practical hydrological work. The underlying theory is often perceived as complicated, and the predictions themselves are often perceived to be difficult to construct and interpret.

In this paper we demonstrate that simple practical approaches are increasingly available to achieve high quality probabilistic predictions in a wide range of practical hydrological prediction applications. Our target audience are hydrologists in research and operations who are familiar with traditional hydrological modelling concepts and would like to extend their expertise to probabilistic modelling. A major focus is on providing guidance for robust descriptions of uncertainty using residual error models. This guidance includes the choice of transformation to handle common features of residual errors (heteroscedasticity, skewness, persistence), on estimation techniques for residual error model parameters, guidance on the relative importance of hydrological parameter uncertainty, and finally techniques to achieve high quality predictions from hydrological models already calibrated using a wide range of common objective functions. A software tool that implements these techniques is provided. The approaches are based on key insights from multiple research papers over multiple years, and their robustness has been shown over numerous catchments.

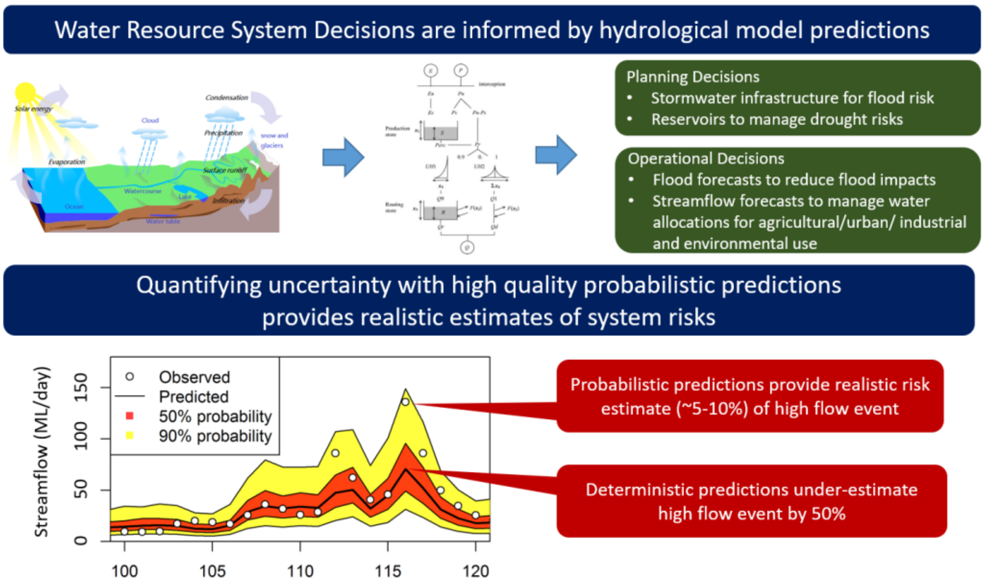

Figure 1. Construction and use of probabilistic predictions in practical hydrological applications

Keywords: *Hydrological modelling, streamflow, predictive uncertainty, probabilistic prediction, residual errors, practical model applications*

Assessment of flood risk predictions based on continental-scale hydrological forecast

Zaved Khan, **Elisabeth Vogel, Julien Lerat, Katy Bahramian, Andrew Frost and Justin Robinson**

Bureau of Meteorology
Email: Zaved.Khan@bom.gov.au

Abstract: The Australian Bureau of Meteorology provides a range of flood warning services, providing flood forecasting and warning services for most major rivers in Australia. As part of those services, the Bureau issues a 'Flood Watch' to provide early advice of a developing situation that may lead to flooding. A Flood Watch provides information about a developing weather situation including forecast rainfall totals, catchments at risk of flooding, and indicative severity where required. Although there is uncertainty attached to a Flood Watch, its early dissemination can help individuals and communities to be better prepared should flooding eventuate. A FloodWatches is typically developed based on a 7-day rainfall forecast from an ensemble of available Numerical Weather Prediction (NWP) models, antecedent soil moisture and dam conditions, and expert meteorological and hydrological input by Bureau of Meteorology staff. This information is used with event-based flood forecasting models to estimate the risk of reaching pre-specified river height thresholds for minor, moderate and major flooding at locations across the continent.

A new national 9 days hydrological forecast system has recently been developed by the Bureau of Meteorology forming part of the Australian Water Outlook suite (see www.bom.gov.au/water/awo). The ouputs provided from that system, based on the Australian Water Resources Assessment Landscape model (AWRA-L), hold potential for application over a range of uses including flood risk.

In this study, the output ensemble forecasts from the forecasting system are tested to explore the potential of use in flood risk predictions. AWRA-L runoff forecasts are investigated to flag potential flood events over the coming 3, 5 or 7 days. The performance of runoff-based forecasts was

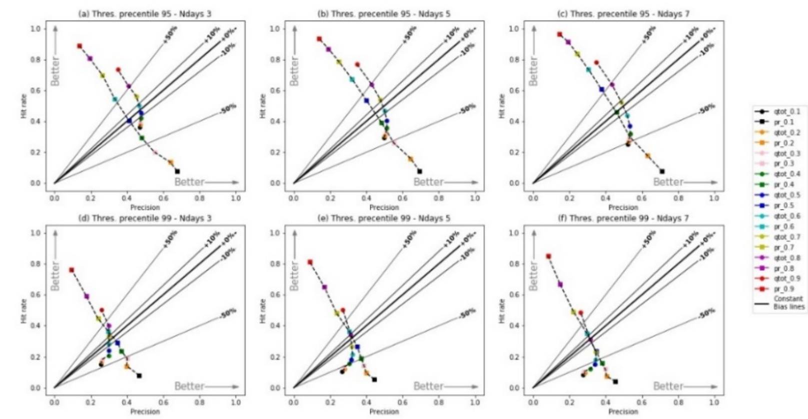

Figure 1. Precision and hit rate metrics for flood watch products using post-processed inputs of ACCESS-G2. Each symbol indicates the average performance of a flood watch across the 75 sites for various proportion of ensemble triggering the event from 10% to 90%. The circle and square symbols show the performance of rainfall and runoff-based products, respectively.

benchmarked against precipitation-based flood risk predictions for recent flood events in Queenlsand (during which hindcast ACCESS-G2 data was available). For these events, rainfall-based flood watch tended to over-predict the number of flood events at the 95% exceedance probability, which led to a high hit-rate, but also positive bias and low precision (See Figure 1). For more extreme flood risk events (defined as exceeding the 99th percentile), we found that rainfall only and runoff based flood watches showed comparable performance in terms of bias and precision. These results highlight the importance of considering catchment conditions for moderate flood events and the potential of using runoff-forecasts for improving the precision of flood risk forecasts. Overall, this comparison confirmed the value of AWRA-L derived flood watch compared to a precipitation-based forecast.

Keywords: *Hydrological forecast, continental scale, flood watch, AWRA-L*

A method to calibrate daily rainfall-runoff models to monthly streamflow data

Julien Lerat [a], **Dmitri Kavetski** [b], **David McInerney** [b] **and Mark Thyer** [b]

[a] *CSIRO Land & Water,* [b] *School of Civil, Environmental and Mining Engineering, University of Adelaide, South Australia*
Email: julien.lerat@csiro.au

Abstract: Conceptual hydrological models that predict streamflow at daily time steps are widely used in water forecasting, water resources planning and operations. Typically, these models are calibrated using daily observed streamflow data. However, in practice there are several common circumstances where observed data is not available at a daily resolution. In particular, a key practical application motivating this work is the operation of large dams. In large dam operation, inflows are typically estimated from (known) dam outflow and water levels by methods such as inverse pool routing. These methods are generally stable at monthly time steps but can become unstable at shorter time steps (e.g. daily) due to the uncertainty in water level data and the storage/volume relationships. Development of robust approaches for calibrating daily rainfall-runoff models to monthly streamflow data is hence of major practical interest.

This study describes an empirical analysis of 508 Australian catchments over two evaluation periods using the GR4J daily hydrological model. It compares the performance attained after calibrating the model to daily streamflow data versus monthly data. Multiple performance metrics are used: fit of the daily and monthly flow duration curve, daily pattern metrics (NSE, correlation, peak timing errors), and long-term bias.

A key finding is that monthly calibration schemes reach comparable performance to daily calibrations for performance metrics such as the fit of daily flow duration curves in low, medium and high flows, with a majority of sites and periods reaching similar or better metric values. This finding holds despite monthly calibration having no access to daily streamflow data. On the other hand, and as expected, monthly calibration performs generally worse than daily calibration for metrics related to daily patterns of the hydrograph, such as NSE, correlation and peak time errors.

However, monthly calibration can degrade the accuracy of estimated timing of flood peaks and, more generally, daily hydrograph patterns. Our results indicate that this limitation can be alleviated by estimating those parameter(s) controlling hydrograph timing using regionalisation from nearby catchments.

Overall, the empirical findings indicate that monthly calibration is a viable alternative to daily calibration when no daily flow data is available. Importantly, the findings hold over a large sample of Australian catchments. Future work on extending the findings to broader classes of rainfall-runoff models is recommended.

Keywords: *Streamflow prediction, rainfall-runoff models, model calibration, monthly streamflow*

IUWM principles incorporated model to improve urban water supply reliability in developing countries

S. S. Mohapatra [a,b], **Meenakshi Arora** [a], **Wenyan Wu** [a] **and M.K.Tiwari** [b]

[a] *Department of Infrastructure Engineering, The University of Melbourne, Melbourne, Victoria, Australia*
[b] *School of Water Resources, Indian Institute of Technology, Kharagpur, West Bengal, India*
Email: smohapatra@student.unimelb.edu.au

Abstract: Urban water supply systems in developing countries like India face unique water-related problems due to changing socio-economic dynamics, pollution of water sources, depletion of limited freshwater availability and climatic change. These challenges include (a) insufficient and unplanned expansion of urban water systems, (b) technical and infrastructural inadequacy, (c) limited water availability and shared water sources among multiple administrative regions, and (d) water loss from the systems in the form of unaccounted-for-water either through physical losses like leakage and metering inadequacy or apparent loss such as tampering and unauthorized water withdrawal. These challenges contribute significantly to intermittency in piped-water supply in India, where piped-water service typically delivers less than 24 hours a day or a particular number of days per week in some cases. It is important to analyze water balance in developing countries so that necessary modifications can be made to make sufficient water available, thus increasing the reliability of water services supplied.

Integrated Urban Water Management (IUWM) is one of the principles applicable to integrated water management in urban areas, and it relies on diversifying water sources, integrating all the parts of the water cycle to produce fit-for-purpose water. Such principles utilize various sustainability approaches based on water conservation, reuse and recycling involving multiple stakeholders, water experts, planners and communities in the decision-making process, and presents potential solutions to achieve supply reliability in developing countries.

Several water simulation platforms have been developed to model urban water supply integrating IUWM principles and have been used largely in developed countries. We developed an IUWM incorporated model using eWater Source Version 5.4.0.11797 to analyze improvement in water supply reliability, with Bangalore, India, as a case study. eWater Source was selected as it is a user-friendly and flexible platform with the potential to integrate the model with other platforms and has vast toolkits availability. Five different supply configurations to incorporate IUWM principles were analyzed and compared to identify the most efficient way to incorporate non-conventional water sources (e.g., harvested stormwater, rooftop rainwater, and recycled wastewater). The supply reliability of the current water supply and improved water supply was then compared.

Results show that each configuration has pros and cons regarding cost and reliability due to the different extent to which the alternative water sources are incorporated. The configuration incorporating all alternative water sources to supply fit-for-purpose water is found out to be the most promising way to incorporate IUWM principles in urban water systems. It offers flexibility in the options of water extraction from different sources based on need and treating them to a quality required for fit-for-purpose use but has high capital and operating cost. The other configurations utilizing alternative water sources can still meet the demands but offers less flexibility of water sourcing options considering climate-dependant (harvested stormwater and rooftop rainwater) and climate-independent (recycled wastewater) sources supplying fit-for-purpose water to meet demands. As compared to the current water supply configuration, all the IUWM incorporated urban water supply configurations produced much higher water supply reliability results.

Keywords: *Integrated Urban Water Management (IUWM), urban water supply systems, developing countries*

The local influence of residential infill on the urban water flows: a multi-city analysis

M. Moravej[a, b], **S. Kenway**[a, b], **M. Renouf**[a, b], **C. Urich**[c, b], **O. Sainsbury**[b, d], **N. Bertram**[b, d] **and G. London**[b, e]

[a] Australian Centre for Water and Environmental Biotechnology (formerly AWMC), the University of Queensland, St. Lucia, QLD, [b] CRC for Water Sensitive Cities, Monash University, Clayton, VIC, [c] Civil Engineering Department, Monash University, VIC, [d] Monash Art Design and Architecture, Monash University, [e] Design School, University of Western Australia
Email: m.moravej@uq.edu.au

Abstract: Infill development is an unprecedented opportunity to reshape cities incorporating innovative design to address urban water challenges such as pluvial flooding, water insecurity, and degraded receiving water bodies. This study aims to address the influence of architectural design (before and after infill) on the urban water flows by studying the water performance of 28 design typologies in three cities of Adelaide, Brisbane, and Melbourne.

Design typologies were categorised based on the scale of infill (e.g. Small Infill vs apartments) and infill typologies: representing before infill or existing case (EX) and two categories for after infill namely business-as-usual (BAU) demonstrating developments under current planning policies and building design codes and Alternative (ALT) designs following Water Sensitive Urban Design principles. We used Site-scale Urban Water Mass Balance Assessment (SUWMBA) tool to estimate urban flows into and out of development sites to quantify the local influence on the urban water cycle.

The results showed design typologies exhibit a varying performance in different cities, calling for city-specific rather than generic designs. BAU infill, in particular, demonstrates the most disruption to the natural hydrology by increasing stormwater discharge up to 442% and decreasing evapotranspiration and infiltration down to 31% and 36% of the flows in the natural landscape. The implication of this disruption on stormwater management (i.e. urban drainage), risk of pluvial flooding, and urban heat was discussed. ALT designs show a lower degree of disruption of natural hydrology while providing more densification compared to BAU. Despite this relative success, all designs failed to restore natural hydrology fully. We argue that improvements in architectural designs combined with Water Sensitive Urban Design technologies (e.g. local harvest of rain and stormwater) to a varying degree are needed to achieve net-zero water impact.

Keywords: *Integrated modelling, water sensitive urban design (WSUD), low-impact development (LID), densification, urban hydrology*

Water security analysis of the Middle River supply system: a *fore*SIGHT application

Culley, S. [a], Westra, S. [a], Bennett, B.[a], Maier, H.R. [a], Newman, J. [b], van der Linden, L.[b] and Irvine, M.[b]

[a] *University of Adelaide*
[b]*South Australian Water Corporation*
Email: sam.culley@adelaide.edu.au

Abstract: Scenario-neutral approaches have become the preferred method of interpreting climate driven impacts on natural and engineered systems when analysing the reliability of water resource systems facing climate change. Scenario-neutral approaches help deal with uncertainty and potential decision paralysis, by stress-testing systems across a range of plausible future conditions, instead of analysing systems under a narrower selection of climate projections. This results in better identification of failure modes and a richer elucidation of system behaviour. A case-study application of a methodology that supports the bottom-up approach—driven by a software tool '*fore*SIGHT'—is presented here. Applied to the Middle River Reservoir system, the scenario-neutral approach adopted here follows three steps to: i) provide insights into system dynamics, ii) reveal modes of failure due to changes in climate, and iii) understand when intervention may be required given multiple lines of evidence.

The Middle River system (situated in Kangaroo Island, South Australia) comprises of a single reservoir with relatively small storage volume relative to the annual catchment inflows, resulting in large seasonal fluctuations in reservoir levels with regular filling in winter and drawdown over the dry season. The reservoir can hold approximately 200 ML more than the mean annual demand (450 ML), which is highly variable year to year. The occurrence of draw down below 6 and 2 m levels were of interest to the stakeholders, as they broadly indicate, the need to augment the water supply due to a decrease in water quality (below 6 m), and the reservoir emptying (below 2 m). The reliability of the water supply system in 2030 was the focus of the analysis, as this aligns with opportunities to upgrade infrastructure.

Observed hydrological data for the Middle River catchment was analysed, and a coupled hydrological, water balance and demand model was used in order to determine a historical baseline of system performance over the period of 1961-2005. When modelling the system in response to the historical baseline as a benchmark of expected performance, it was found that in dry years the demand can be high enough to draw down the reservoir below 6 m. The modelled probability of that failure under a historical climate was ~2%. It was also found that following this period of stationary climate there has been an observed increase in PET of 8.3%, indicating that the system is already experiencing a 'changed' climate compared to the historical baseline.

A climate stress-test of the Middle River water supply system following the *fore*SIGHT framework demonstrated that the system is sensitive to annual changes in rainfall and PET. These metrics both influence supply and demand, with decreases in rainfall primarily affecting streamflow, and increases in PET increasing the demand placed on the system. In many of these failures, the reservoir had not filled the previous year, therefore providing little warning to enable water augmentation strategies to be put into place. Under more extreme changes in climate, the reservoir cannot fill multiple years in a row, leading to multi-year failures.

To establish an understanding of how the climate might have changed in 2030 relative to the historical baseline, multiple lines of evidence were considered including multiple sources of climate model projections for the year 2030, and the recent trend in observed PET. It was found using the scenario-neutral approach that in the climate conditions projected for the year 2030 the probability of failure of the reservoir dropping below 6 m could increase from 2% to 7-8%. Further, the observed trend in PET suggests the probability of failure may have already increased to 5%. This highlights a significant system sensitivity to relatively small changes in climate.

Keywords: *Scenario-neutral climate change impact assessment, climate stress-test, water security*

EXTENDED ABSTRACT ONLY

Integrated framework for rapid climate stress testing of river systems

Keirnan Fowler[a] , **Natasha Ballis**[a], **Avril Horne**[a], **Andrew John**[a], **Rory Nathan**[a] and **Murray Peel**[a]

[a] *Environmental Hydrology and Water Resources Group, Department of Infrastructure Engineering, University of Melbourne, Parkville, 3010, Australia*
Email: fowler.k@unimelb.edu.au

Abstract: Bottom-up methods are increasingly used to assess the vulnerability of river systems to climate change. Central to these methods is the climate "stress test", where the system is subjected to various climatic changes to test for unacceptable outcomes. We present a freely available framework for climate stress testing of river systems, summarised in Figure 1. The framework is on a monthly timestep, suitable for systems whose dominant dynamic is seasonal or longer (e.g. water resource systems with carry-over storage). This timestep is a point of difference from existing daily-timestep tools. The framework integrates multi-site stochastic climate generation with perturbation methods and in-built rainfall-runoff modelling, offering:

- Rapid runtimes afforded by parsimonious stochastic generation tools. Runtimes are sufficiently short to enable detailed climate stress testing by those without access to a supercomputer;
- Specialised treatment of the low frequency dynamics of precipitation, including the ability to perturb this behaviour, allowing realistic representation of multi-year drought dynamics;
- A wide array of options including single- or multi-site stochastic generation and perturbation of up to five stressors simultaneously, namely: P_{mean}, T_{mean}, $P_{low\ frequency}$, $P_{seasonality}$ and rainfall-runoff relationship; and
- Integration of all analysis tools required to generate and perturb stochastic data for stress testing, including generation of streamflow data via an inbuilt rainfall-runoff model. Together with the low computational requirements and option to be run in Octave freeware, the 'one-stop-shop' aspect of the framework facilitates uptake of stress testing methods even by first-time users.

We demonstrate the framework on the 40,000 km^2 Goulburn-Broken-Campaspe-Loddon system in Victoria, Australia. Hydroclimatic timeseries are generated for seven subareas of this system, and then a stress test is performed, examining the vulnerability of allocation reliability and ecosystem health to plausible future changes in climate (using joint river systems and ecological models external to the framework). The Matlab/Octave code is available for download from https://github.com/kjafowler/rapid-climate-stress-testing.

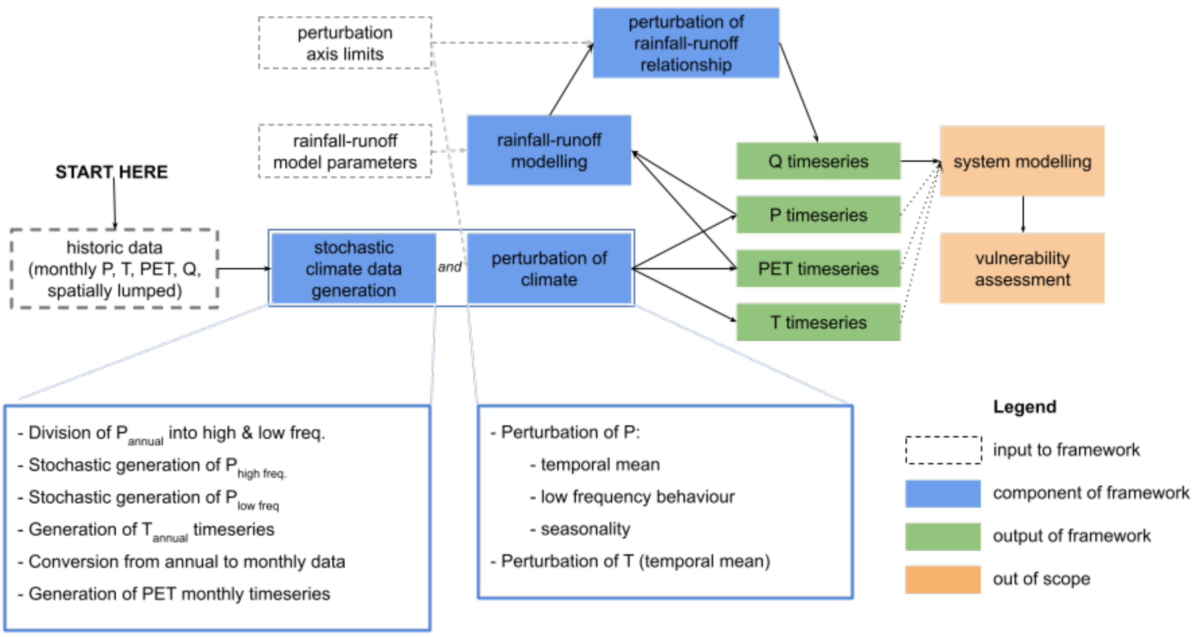

Figure 1. Visual summary of the stochastic generation framework

Keywords: *Climate change, water resources, bottom up, climate stress test, scenario neutral*

Uncertain Futures website: building reference materials for decision making in the face of multiple plausible futures

Joseph Guillaume [a], **Sondoss Elsawah** [b], **Hannah Feldman** [c], **Baihua Fu** [a], **Tony Jakeman** [a], **Holger Maier** [d], **Caroline Rosello** [a], **Tony Weber** [a, e] and **Fateme Zare** [b]

[a] *Institute for Water Futures and Fenner School of Environment & Society, The Australian National University, Canberra, ACT 2601, Australia*
[b] *Capability Systems Centre, University of New South Wales, Canberra, Australia*
[c] *Institute for Water Futures and School of Cybernetics, The Australian National University, Canberra*
[d] *School of Civil, Environmental & Mining Engineering, University of Adelaide, Adelaide, South Australia*
[e] *Alluvium Consulting, Brisbane*
Email: joseph.guillaume@anu.edu.au

Abstract: This presentation introduces the Uncertain Futures website (https://uncertainfutures.github.io/), a community effort to synthesise reference materials about theory, software tools, and case study materials for decision making in the face of multiple plausible futures. While generally applicable, the ideas are specifically illustrated with a focus on water modelling and management, and we gratefully acknowledge seed funding from the Queensland Water Modelling Network (QWMN).

The intention is for the website to provide reference materials in a simple but attractive form conducive to the creation of products for training and awareness raising. The website is targeted at anyone interested in the idea of decision-making using scenarios/in the face of multiple plausible futures. While future efforts might build, a tutorial or course using this content, for example, in the short term the intention is for someone browsing through the website to come across new ideas or connections between ideas, with the design of the website encouraging the reader to go down a rabbit hole and find things they did not know about. The range of pages available should cater to both more and less technical audiences, with links between pages accordingly. The collected materials are provided with a Creative Commons Attribution license, explicitly encouraging collaborative development of added value products. The website is hosted on the software development and version control website GitHub and welcomes contributions.

The website follows "design pattern" principles that here consists of certain key elements: decomposing a problem situation into design elements, making links between elements explicit, and encouraging users to mix and match components to form their own understanding of the tools available. The website provides three types of pages: theory, including both concepts and named methods; software tools; and examples, including both general problems and specific case studies.

The home page provides links directly to several concepts, and index pages for each type of page provide short summaries, also acting as a glossary. The website allows for pages under construction (that only include summaries) in order to ensure that concepts are represented even if full content has not been compiled. Each page for a concept, method or tool, discusses the purpose and requirements, describes what is involved in using it, and provides links to case studies and further resources.

A potential user has five potential entry points from which to explore the reference material provided: 1) links channelling the reader to the page on "multiple plausible futures", which serves as an introduction to the topic, 2) searching for a known concept, 3) browsing through documented theory pages to come across something new, 4) browsing through software tools, and 5) browsing through general problems and case studies of interest. Dense interconnection between pages encourages the reader to then follow their nose to learn more detail about interconnected concepts.

We hope to continue to develop the Uncertain Futures website to support development and adoption of robust and adaptive decision making practices in Australia and abroad.

Keywords: *Uncertainty, multiple plausible futures, scenario analysis, design patterns*

Stress testing climate adaptation for environmental water in the Goulburn River, Victoria

Andrew John[a], **Avril Horne**[a], **Rory Nathan**[a], **Keirnan Fowler**[a], **J. Angus Webb**[a] **and Michael Stewardson**[a]

[a] *Environmental Hydrology and Water Resources Group, Department of Infrastructure Engineering, University of Melbourne, Parkville, 3010, Australia*
Email: andrew.john@unimelb.edu.au

Abstract: Climate change presents significant threats to freshwater ecosystems, challenging the implementation and success of environmental flows worldwide. Large uncertainties in precipitation changes and flow responses, combined with a history of assumed climatic stationarity in environmental flows assessments, mean that robust options are needed to protect ecosystem outcomes. Stress testing methods offer a way to test system sensitivity to uncertain inputs associated with climate change. By beginning with an exploration of river system vulnerability, environmental flows can be designed or augmented to improve robustness against a range of plausible climate futures. We present the results of stress testing environmental outcomes for the Goulburn River, Victoria, which is part of a large complex system delivering water primarily to northern Victoria. Given the limitations of current water management in supporting environmental outcomes under climate change, we tested three different adaptation options individually and in combination, for a total of seven options.

The Goulburn River provides a large share of inflows to the Murray-Darling Basin. The river has substantial ecological values and supports multi-billion-dollar agriculture. Ecological outcomes are supported by actively managed environmental flows, the management of which responds to natural variations in climate by adjusting the priority of different flow components. For example, in dry years, low flows are prioritised to sustain key refuge habitat; however, under a drying climate, it will be more difficult to deliver ecologically important high flow components in spring and autumn, which will adversely impact on ecological responses. In addition, existing river capacity issues mean it is difficult to deliver these high flows even assuming sufficient water allocations.

Using a stochastic data generation framework and simplified water resource model that enables rapid scenario generation and simulation, we investigated current system vulnerabilities through three key output metrics: 1) the *reliability* of primary water entitlements, 2) *shortfalls* in meeting environmental flow recommendations, and 3) projected *ecological outcomes* based on using mechanistic models of twelve key ecological endpoints. We then evaluated the effectiveness of three different adaptation options in terms of their ability to improve outcomes across a range of climate changes considered in the stress test. These adaptation options considered were: 1) increasing the available environmental entitlement, 2) relaxing river capacity constraints, and 3) increasing the priority of some flow components in the seasonal water allocation process. It was found that increasing environmental entitlements yielded the largest benefits in drier climate futures, whereas relaxing river capacity constraints (allowing more targeted delivery of environmental water) offered more benefits for current and wetter climates. Combining both these options led to greater than additive improvements in allocation reliability and reductions in environmental water shortfalls, and these improvements were achieved across a wider range of climatic conditions than possible with either of the individual options.

The assessment of adaptation effectiveness was found to be dependent on the adopted performance metric. Using the ecological models demonstrated that the tested adaptation options were effective for drying climates but could lead to worse ecological outcomes in wetter climates. The latter impacts were not evident using the shortfalls metric. Ultimately, there was a degree of plausible climate change beyond which none of the adaptation options were able to mitigate the adverse impacts on ecological outcomes. This study demonstrates an important step for environmental flow assessments: evaluating the feasibility of environmental outcomes under climate change, and the intervention options that prove most robust under an uncertain future.

Keywords: *Environmental flows, climate change adaptation, freshwater ecosystems, climate stress testing, mechanistic modelling*

KEYNOTE

EXTENDED ABSTRACT ONLY

The challenges of modelling climate change impacts in non-linear water resources systems

Fiona Johnson[a], **Clare Stephens**[a,b], **Chris Chen**[c,d], **Martin Krogh**[e] **and William Glamore**[c]

[a] Water Research Centre, School of Civil and Environmental Engineering, University of New South Wales, Sydney, 2052, Australia, [b] Hawkesbury Institute for Environment, Western Sydney University, Richmond, 2753, Australia, [c] Water Research Laboratory, University of New South Wales, Manly Vale, 2093, Australia, [d] Water Modelling and Advice, WaterNSW, Sydney, 2150, Australia, [e] Science, Economics and Insights Division, Department of Planning, Industry and Environment, Parramatta, 2124, Australia
Email: f.johnson@unsw.edu.au

Abstract: Assessing climate change impacts in complex and non linear systems is challenging because of system feedbacks, poor conceptual understanding of the important ecologic and hydrologic drivers of the system, inability to holistically model all of these processes and the impacts of natural variability over multiple timeframes ranging from weeks to years through to decades. This complexity means that a variety of methods should be considered that can identify threshold behaviours and stakeholder-relevant impacts. This presentation will present an overview of recently developed methods that can address some of these issues, using the Thirlmere Lakes National Park climate change assessment as a case study.

Thirlmere Lakes National Park which is a system of five lakes south west of Sydney. Declines in water levels in the lake system over the last two decades led to community concerns about the sustainability of the lake system. The Thirlmere Lakes Research found that climate variability explained between 80 to 98% of the long term variations in lake levels, suggesting that the lakes may be vulnerable to anthropogenic climate change in the future (Chen et al. 2021). In this case study, two methods were used to investigate climate change impacts on the lake system. Firstly regional climate model (RCM) simulations available from the NSW Government NARCLiM project were bias corrected (Mehrotra et al. 2018). Because of the limited number of RCMs and driving GCMs used for the transient NARCLiM simulations (3 GCMs and 2 RCMs), a bottom up climate change assessment was also carried out to understand potential threshold behaviours in the lake system that not been sampled in the NARCLiM models.

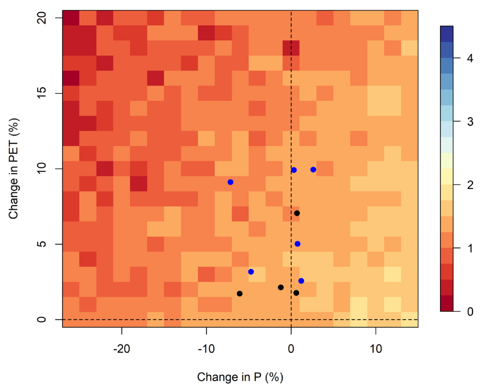

Figure 1. Median simulated water depths (m) for Lake Gandagarra for changes in annual rainfall and evapotranspiration. Dashed lines show historical climate, black (blue) dots show NARCLiM RCP4.5 (RCP8.5) projections.

The impacts of climate change were evaluated by focusing on key properties of interest to the community and for long term management of the system. The NARCLiM simulations suggest that water levels will be slightly higher under RCP4.5 and similar to historical levels for RCP8.5. The range of bottom up simulations included far more cases with drier conditions (Figure 1) and when these are coupled with increases in evapotranspiration, up to 80% of the scenarios lead to lower median water levels in the lakes than historically. The bottom up climate change assessment allowed a far wider range of future outcomes to be explored to understand the varying responses of the five lakes. The project is particularly interesting because the storage in the lakes amplifies biases in the hydrological modelling and highlights areas to focus on in future method development.

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Keywords: *Climate change, water balance model, lakes*

EXTENDED ABSTRACT ONLY

A multi-modelling framework to stress-test water resource systems under change

Ruby M. R. Leigh[a], Matthew J. Knowling[a], Seth Westra[a], Bree S. Bennett[a], Aaron C. Zecchin[a], Holger R. Maier[a], Mark A. Thyer[a] , David McInerney[a] , Sam A. Culley[a], Michael Leonard[a], and Anjana Devanand[b]

[a] *School of Civil, Environmental and Mining Engineering, University of Adelaide, Adelaide, 5005, Australia*
[b] *Climate Change Research Centre, The University of New South Wales, New South Wales, 2052, Australia.*
Email: ruby.leigh@adelaide.edu.au

Abstract: Water resource systems are dynamic, and characterised by complex interactions between hydrologic, ecologic and infrastructure components. In order to effectively stress-test the system for a range of future climates these components require representation within an integrated model. Whilst qualitative approaches are valuable for problem specification, stress-tests of water resource systems typically take a quantitative approach given the complexity of the processes, with the outcome being a quantitative mapping between climate scenarios and measures of system 'performance'. This study takes a unique approach in which a system dynamics model is developed as an 'emulation' of a collection of more detailed, but incompatible, process-based models, in order to explore water resource system security under change.

A case study of the Barossa region is presented, where changing climate conditions are likely to place significant stress on water security in the region, as evidenced by recent water supply failing to meet historical irrigation demands. The component models include a conceptual rainfall runoff model, representing surface water dynamics such as streamflow, farm dam volume and surface water extraction; a numerical groundwater model representing groundwater processes such as recharge, groundwater storage, groundwater evaporation and baseflow; and a simple irrigation demand model that is driven by climate variables and calibrated to recent water use data. Regression relationships derived from the component models are implemented in the system dynamics model, which allows the system to be efficiently and flexibly stress-tested for a range of future climates, as well as to explore potential viable future system configurations. Exploration of the systems dynamics approach for the mid-complexity Barossa region provides a basis for investigations of other, more complex, systems.

Keywords: *System dynamics modelling, climate stress testing, bottom-up, scenario-neutral*

Uncertainty, sensitivity and scenario analysis: how do they fit together?

H.R. Maier [a], J.H.A. Guillaume [b], C. McPhail [a], S. Westra[a], J.H. Kwakkel [c], S. Razavi [d], H. van Delden[e,a], M.A. Thyer [a], S.A. Culley [a] and A.J. Jakeman [b]

[a] School of Civil, Environmental & Mining Engineering, University of Adelaide, Adelaide, South Australia, [b] Institute for Water Futures and Fenner School of Environment & Society, The Australian National University, Canberra, Australia [c] Faculty of Technology, Policy and Management, Delft University of Technology, the Netherlands, [d] School of Environment and Sustainability, University of Saskatchewan, Canada, [e] Research Institute for Knowledge Systems, Maastricht, the Netherlands
Email: holger.maier@adelaide.edu.au

Abstract: Dealing with uncertainty is becoming increasingly important in model-based decision support. Various methods have been developed in order to do this, including uncertainty, sensitivity and scenario analysis. Although these different methods serve their purpose, the availability of a large number of methods can make it difficult for practitioners to understand the similarities and differences between them and when the use of one is more suitable than another, resulting in confusion. In addition, researchers often identify with belonging to a group dealing with a particular approach, which can lead to a lack of cross-fertilisation and understanding.

In order to assist with bridging the gap between researchers working on different approaches to dealing with uncertainty and eliminate confusion for practitioners, the objective of this paper is to examine the relationship between uncertainty, sensitivity and scenario analysis in the context of model-based decision support, and to take the first steps towards establishing common ground between these methods and assess the contexts under which they are most suitable.

This is achieved by conceptualising the various methods as different approaches to "sampling" the hyperspace of model inputs, although this is done from different perspectives and for different ends (Figure 1). It is therefore also necessary to think about the assumptions each method is making about the space being explored, and there are benefits to be gained in thinking about how best to sample the space for each purpose.

The approaches identified in this conference paper provide a first level of coarse characterisations. Further refinements in categorisation is possible (with the differentiation between narrative and stress testing scenarios as a first example), and likely to be useful. There are connections to be made to other disciplines, such as philosophy and decision theory, regarding the assumptions each method makes.

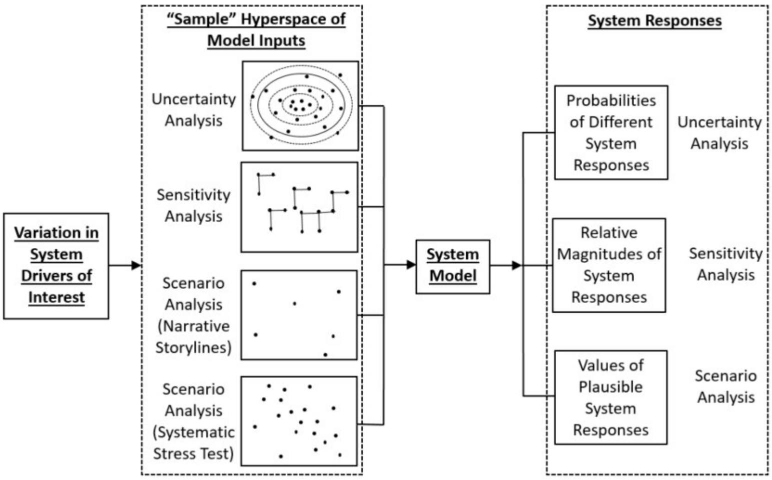

Figure 1. Illustration of how uncertainty, sensitivity and scenario analysis represent different ways of "sampling" the hyperspace of inputs to system models.

Keywords: *Uncertainty analysis, sensitivity analysis, scenario analysis, sampling, guidance*

Groundwater flow modelling of Al-Jizzi aquifer, Oman

Javed Akhter [a], **Ahmad Sana** [b] **and Syed M. Tauseef** [a]

[a] Department of Health, Safety, Environment and Civil Engineering, University of Petroleum and Energy Studies, Dehradun, 248007, India, [b] Department of Civil and Architectural Engineering, Sultan Qaboos University, PO Box 33 Muscat, 123, Oman
Email: akhtar_16@rediffmail.com

Abstract: The northern Al Batinah plain in Sultanate of Oman contains substantial groundwater resources that have been widely used by generations for their irrigation, industrial and domestic water supply purposes. Ground water aquifers in the region are fed by infrequent and minimal rainfall of an average of 100 mm per year, and which are over abstracted and facing water depletion. A constant water deficit caused by excessive pumping in the region has caused the water quality to deteriorate owing to seawater intrusion. Several farms have been deserted and many others are currently at risk. Sana & Shibli (2003) studied the salinity intrusion in Al-Jizzi aquifer (located in Al-Batinah region) using MODFLOW. A coarse grid (average cell sizes of about 520m x 620m) was employed. In the present study a refined grid (average cell sizes: 33.4 m × 42.8 m) is used which is further refined at the pumping wells to improve the model precision. Also, the conceptual model has been improved considering the bore-log data in the vicinity of the coast. Calibration of the two-layer steady-state conceptual model was carried out using the observed head in the monitoring wells for the year 2000. The model domain was covering nine observation and 22 pumping wells which were spread in five different zones of the model. Field data in the form of the observed water head was available and hydrogeological data which was available from the previous studies was used for calibration of the model. Geo-hydrological parameters like hydraulic conductivity and vertical anisotropy were by manually calibrating in steady state condition. Further, the model was calibrated and validated in the transient condition for the year 2001-2017.

The model showed good agreement of the calculated head with the observed water head in the study area (difference between the observed and calculated head was less than 2m). A global sensitivity analysis carried out for the hydraulic conductivity for both the layers affecting the water heads to estimate the uncertainties for this model parameter on the numerical results. Predicted water levels provide an indication of the magnitude of the change in water levels that can be expected to occur if the predicted recharge and abstraction rates are implemented. The calibrated model was used to predict two different scenarios of incremental pumping and reduced pumping by 10 – 30 % and 5 - 10% of the pumping rates used in the year 2017. The model predicted an average fall of 2.0 m in groundwater table in the study area within the next 22 years (year 2040) if groundwater abstraction continues at the present rate. If the pumping is reduced by 10 %, it could help to reclaim the water level. The study results could be useful for decision makers and practicing engineers for better management of groundwater resources in the arid regions.

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Keywords: *Coastal aquifers, numerical modelling, ground water flow, MODFLOW.*

Surface-groundwater causal interactions identified with convergent cross-mapping

G. Bonotto [a], T.J. Peterson [a, b], K. Fowler [a], Andrew W. Western

[a] Department of Infrastructure Engineering, School of Engineering, The University of Melbourne, Melbourne, Victoria
[b] Department of Civil Engineering, Monash University, Clayton, Victoria, Australia
Email: gbonotto@unimelb.edu.au

Abstract: Although it is common to conceptualise groundwater as causally linked to streamflow, it remains challenging to quantify the actual strength and direction of the interactions. Interactions between groundwater and surface water are dictated by multiple processes that are often difficult to measure, insufficiently monitored, and inaccurately conceptualized within hydrologic models. Therefore, hydrological modelling and water management often rely on expert knowledge to draw causal links between groundwater and surface water (or vice versa).

In this study, we present the first application of Convergent Cross-Mapping (CCM) to identify causal interactions between streamflow and groundwater head. Widely used in biology and ecology, CCM is a non-parametric method to identify causality in nonlinear dynamic systems. Here the only required inputs to analyse causality between surface water and groundwater are hydrograph time-series, so it may be an attractive alternative or complement to field-based studies of causality.

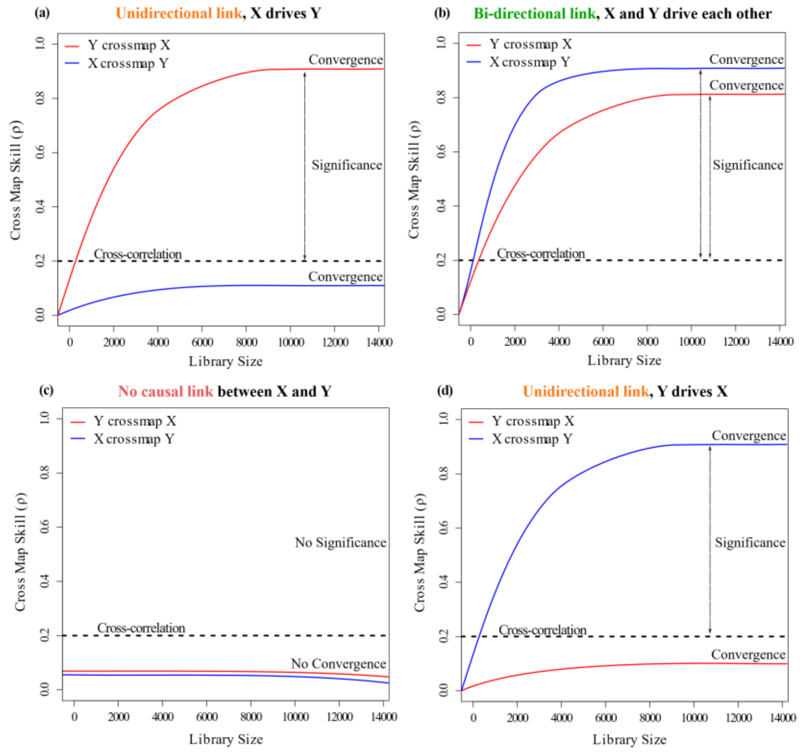

Figure 1. Explanatory example of convergent-cross mapping results and interpretation.

To distinguish between simple correlation and causation using convergent cross-mapping (Figure 1), it is necessary to observe convergence in the cross-map skill (i.e. if larger "library sizes", longer time-series, yield increasingly larger correspondence between the shadow manifolds). Moreover, the cross-map skill (ρ) at full library size should be significant to avoid being confounded as causal influence and, therefore, it was compared against CCM results for surrogate time-series and to cross-correlation. The results were sensitive to record length and period analysed (i.e. wet/dry periods). Moreover, the outputs of the study largely agree with a priori perceptual understanding of the study areas. As expected, bores near valley bottoms drive streamflow more than those on hillsides and hilltops, and aquifer properties play a key role. Overall, this study shows the applicability for Convergent Cross-Mapping to unlock valuable information from groundwater and streamflow hydrographs alone, with relevance to a wide range of applications including hydrological model development, contamination, and river restoration studies.

Keywords: *Surface-groundwater hydrology, Convergent Cross-Mapping, nonlinear dynamic systems*

Mathematical modelling for calcite dissolution in a managed aquifer recharge system

Philip Cole, Ruidi Yang, Shurui Yi, John Boland and Bronwyn Hajek [a]

[a] *UniSA STEM, University of South Australia, Mawson Lakes, 5095*
Email: colpw001@mymail.unisa.edu.au, yanry025@mymail.unisa.edu.au, yiysy003@mymail.unisa.edu.au

Abstract: Managed aquifer recharge (MAR) systems are frequently used as a storage for the re-use of recycled water. For MAR systems targeting limestone aquifers, calcite dissolution can occur when recycled water is injected. Therefore, it is important to monitor the degree of dissolution, because excessive calcite dissolution may lead to an increase in aquifer transmissivity, a greater zone of injected water, and instability in the production wells. In previous research in the literature on calcite dissolution and MAR projects, the extent of dissolution has been calculated by assuming that the rock is dissolved as a solid block in the shape of a cylinder centred on the open well within the aquifer, and no spatial dissolution has been taken into account. As a part of our UniSA Mathematics Clinic project, we estimated the mass of dissolved calcium and built a spatial distribution model of calcite dissolution.

Water extracted from a production well is a mixture of injected water and native groundwater. Using chloride as a tracer, we developed tools for calculating the mixing fraction (that is, the proportion of the extracted water that originated from injection) and applied these to a case study. Results showed that the mixing fraction was, on average, about 84% between 2015 and 2020, with 16% being groundwater. Using these results, the mass of calcium in the extracted water that originated from injection and the mass of calcium resulting from mixing with the native groundwater can be calculated based on the given corresponding calcium concentrations and volumes. The mass of dissolved calcium is calculated by subtracting the mass attributed to mixing and injection from the calcium mass extracted (Figure 1).

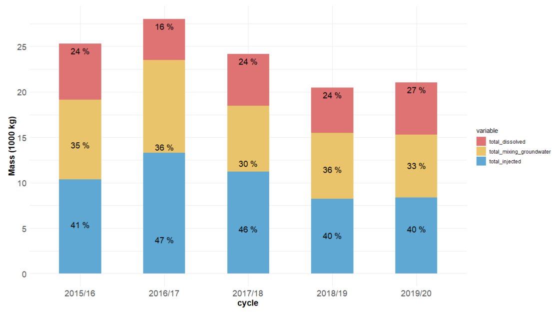

Figure 1. Extracted mass of Ca^{2+} attributed to calcite dissolution (red), mixing (yellow) and injection (blue).

Using the results of that calculation, we built a spatial distribution model of calcite dissolution. In contrast to previous models, we assumed the density distribution of dissolved calcium follows a normal distribution curve,

$$d(r) = \alpha e^{-r^2/(2\sigma^2)},$$

where r is the distance from the centre of the well, σ is one standard deviation, and assuming 3σ is the farthest distance that the injected water can travel from the centre of the production well before extraction. Assuming constant porosity p of the limestone, the extent of travel of the injected water (3σ) can be calculated using

$$\text{Volume of injected water} = \pi(3\sigma)^2 hp,$$

where h is the height of the aquifer, and assuming knowledge of the total volume injected. This calculation is performed for each cycle. Using the solid of revolution formula to integrate the dissolution distribution over the volume of the cylinder, the total mass of dissolved calcium in one full cycle (that is, injection and extraction) can be expressed as

$$\text{Total mass of dissolution} = 2\pi h \int_0^{3\sigma} r d(r)\, dr.$$

Knowing the mass of calcium dissolved over time will help maintain the well stability in the long term.

Keywords: *Aquifer, calcite dissolution, managed aquifer recharge, spatial distribution models*

EXTENDED ABSTRACT ONLY

Groundwater sensitivity to climate across Australia

X. Fan [a,c,d], **T.J. Peterson** [b,a], **B.J. Henley** [a,e,f,g] **and M. Arora** [a]

[a] Department of Infrastructure Engineering, University of Melbourne, Australia [b] Department of Civil Engineering, Monash University, Australia, [c] Climate and Energy College, University of Melbourne, [d] Institute of Applied Geosciences, Division of Hydrogeology, Karlsruhe Institute of Technology, Germany, [e] School of Earth, Atmosphere and Environment, Monash University, [f] Securing Antarctica's Environmental Future, Monash University, [g] ARC Centre of Excellence for Climate Extremes, Monash University
Email: xinyangf1@student.unimelb.edu.au

Abstract: Many studies have attempted to project the impact of climate change on groundwater. However the fifth Assessment Report of the IPCC (Jimenez-Cisneros et al. 2014) states that it is still poorly understood how groundwater level and recharge has and will be impacted by climate change, most likely because of the confounding influence from multiple drivers (e.g. climate, pumping and land cover change) and the limited groundwater observation record. This study aims to contribute to this gap by quantifying the groundwater sensitivity at unconfined groundwater sites where have been primarily driven by climate, and not other drivers such as pumping.

The climate-driven sites were identified using *HydroSight* (Peterson et al., 2014, 2019), a time-series groundwater hydrograph package. A total of 5077 long-term hydrographs were modelled. The only driver simulated was climate (precip., PET), and those with a coefficient of efficiency >0.9 were deemed as being driven primarily by climate, and not pumping or land cover change. In total 336 sites were found driven by the climate, with 245 in Victoria.

The groundwater level and recharge sensitivity to precipitation and potential evapotranspiration was then quantified using a multilinear regression approach adapted from the streamflow elasticity (Chiew, 2006). Results show that nearly one fifth (n=72) of sites in Australia are highly sensitive to precipitation, with a 1% change in precipitation producing >0.5 m change groundwater level. The most sensitive sites are located in southwest Western Australia and southeastern Australia, though there is notable spatial variability. Conversely, the groundwater recharge sensitivity shows a higher spatial consistency. Within Victoria, it gradually increases from north to south (Fig. 1). Overall, by quantifying the sensitivity of groundwater level and recharge to historic climate variations, this study allows identification of the regions throughout Australia most vulnerable to a given change in precipitation and or evapotranspiration and hence more targeted climate change mitigation and adaptation.

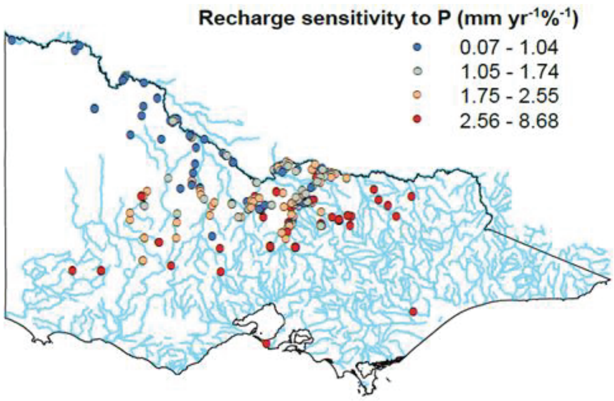

Figure 1. The groundwater recharge sensitivity to precipitation at the climate-driven sites in Victoria.

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Keywords: *Groundwater sensitivity, recharge, climate change*

Modelling stream depletion due to groundwater extraction with a lumped conceptual hydrological model

M Finger[a] and S Mariyapillai[a]

[a] *Department of Environment Land Water and Planning*
Email: Michael.Finger@delwp.vic.gov.au

Abstract: Daily stream depletion impacts on waterways due to groundwater extraction were modelled using a lumped conceptual groundwater model. This approach extends the applicability of streamflow depletion impacts estimated using analytical and numerical groundwater methods to continuous daily streamflow modelling with an appropriate temporal pattern. This approach will improve accuracy of estimation of water available in the stream and provide adequate tools to inform water resource management.

Conjunctive modelling of surface water and groundwater processes and impacts of extraction are important tools to inform water resource management in systems with relevant groundwater surface water connectivity. While analytical models are widely used, they typically assume constant stream stage (Brunner et al. 2011). Coupled numerical groundwater models can represent these processes however it is data and resource intensive. While the constant stage methods may be suitable over longer time periods where water availability is less relevant, they are not immediately compatible with daily streamflow modelling.

Lumped conceptual hydrological models are widely adopted to estimate streamflow used in water resource models. Many of these models include relevant groundwater processes including recharge, conceptual groundwater storage and baseflow. The widely used Sacramento rainfall runoff model (Burnash et al, 1973) was modified to incorporate representation of groundwater. This was achieved by including an additional process to remove water from the Lower Zone Free Water Primary store.

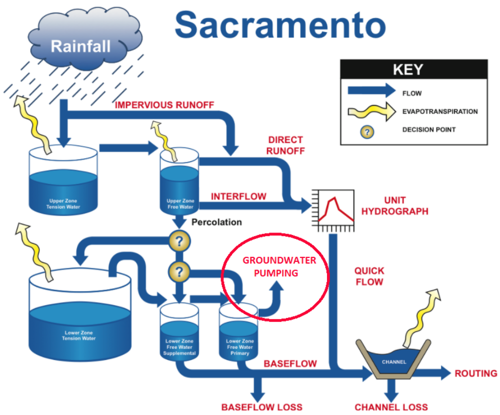

Figure 1. Modified Sacramento Model (modified from eWater)

The method can accept coarse streamflow depletion estimates from analytical methods and numerical groundwater models that represent processes dependent on aquifer properties and spatial relationships. A tributary catchment in the Ovens River valley was selected as a groundwater model using MODFLOW with Streamflow-Routing package that considers stream dynamics was available. The MODFLOW results were simplified by applying streamflow depletion factors estimated by the numerical model to the daily pumping timeseries. The new method was then applied to test ability to independently represent water availability constraints.

The modified Sacramento model was configured with historic pumping impacts and calibrated to observed streamflow data. A composite log NSE Daily and log Flow Duration objective function was selected to prioritise fit to low flows and optimised using SCE (Duan et al. 1992 and Soroonshian et al. 1993).

The calibrated model gives historic streamflow. The parameterised model was then configured with zero and current level of development groundwater impacts to produce (i) unimpacted streamflow, (ii) current level of development impacted streamflow. The difference between the two scenarios is a daily timeseries of the current level of development streamflow depletion that considers water availability constraints.

For the trial catchment, it was found that the modified Sacramento model showed the ability to appropriately represent seasonality of streamflow depletion. The comparison could not be undertaken on the mainstem Ovens River as stream leakage and localised extraction are significant and these processes are not able to be represented in the lumped conceptual model. A future improvement including bidirectional flow between the channel and groundwater store warrants further investigation.

In conclusion, the method can be applied with minimal additional data and resources to produce a reasonable estimate of daily streamflow depletion where the conceptual model is appropriate.

Keywords: *Groundwater, groundwater surface water interaction, hydrological modelling*

An investigation of the role of infiltrated stormwater on evapotranspiration

Abolfazl Poozan [a], **Meenakshi Arora** [a], **Matthew James Burns** [b] **and Andrew William Western** [a]

[a] *Department of Infrastructure Engineering, University of Melbourne, Victoria 3010, Australia*
[b] *School of Ecosystem and Forest Sciences, University of Melbourne, Victoria 3121, Australia*
Email: apoozan@student.unimmelb.edu.au

Abstract: Urbanization involves replacing native soils with impervious surfaces. This changes the water balance in catchments, leading to severe alterations to both low and high flow regimes. A common impact observed is reduced baseflows due to decreased infiltration and thus groundwater recharge. Use of Water Sensitive Urban Design (WSUD) measures are central to mitigating these flow impacts. The stormwater is infiltrated to the ground through infiltration systems in urban landscapes to recharge groundwater and improve stormwater quality through porous media filtration. This is thought to recharge the baseflow where infiltration systems are located upslope of streams. However, this goal may not be achieved in the presence of deep-rooted vegetation downslope as evapotranspiration likely intercepts infiltrated stormwater (a schematic model is shown in Figure 1).

This study aimed to investigate the impact of infiltration basins on evapotranspiration using a modelling approach. We used MIKE SHE to simulate groundwater flow and vegetation downslope of a constructed infiltration basin located in the north-east of Melbourne, Australia. A fixed head boundary condition at the upslope boundary was used to represent the infiltration basin. The model was calibrated and validated against observed data. The first three years of water level data set was used for calibration and the next one year for validation. The model was also run for two years before starting the simulation to ensure that the results are independent of initial conditions. The results showed that the model is able to predict groundwater dynamics, and there is a good agreement between simulated and observed depth to groundwater in the bores located between the basin and stream for calibration and validation periods.

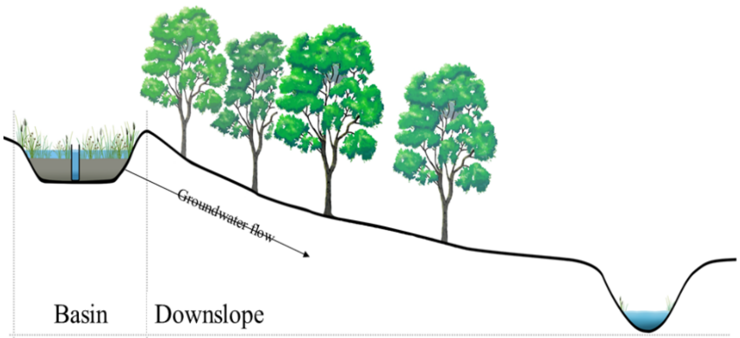

Figure 1. A conceptual model of the potential role of infiltrated stormwater on evapotranspiration

The result showed that transpiration (74%) and interception loss (24%) made the highest contribution to total evapotranspiration at the studied site. The results also showed that there is a reasonable agreement between modelled transpiration and sapflux data; however, sapflux data showed relatively higher seasonal variation. It can be concluded that the performance of the model is satisfactory based on several performance criteria, and the model can be used to investigate the role of the infiltrated stormwater on evapotranspiration.

We then calculated the amount of evapotranspiration in the presence and absence of the infiltration basin upslope. The results showed that the amount of evapotranspiration would increase in warmer months in presence of the infiltration basin. The results also showed that evapotranspiration decreases around 13% on average in the simulation period when there is no infiltrated stormwater upslope. Therefore, infiltrated water alters the amount of transpiration in warmer months due to the change of soil moisture availability. This suggests that the increased transpiration due to the presence of infiltration systems can improve trees' health and bring microclimate benefits, such as urban cooling. However, this also indicates that vegetation downslope likely consumes the infiltrated water which, in some cases, aims to recharge the stream baseflow. Therefore, it is best to implement infiltration systems close the waterways if increasing the baseflow is the main objective.

Keywords: *Baseflow, infiltration, urban, infiltration basin, stream*

Bayesian groundwater vulnerability assessment

Nasrin Taghavi [a] **Robert K. Niven** [a] **David J. Paull** [b] **and Matthias Kramer** [a]

[a] School of Engineering and Information Technology, The University of New South Wales, Canberra ACT 2600, Australia; [b] School of Science, The University of New South Wales, Canberra ACT 2600, Australia
Email: r.niven@adfa.edu.au

Abstract: Groundwater is a vital resource of water supply throughout the world, and subject to an increasing risk of pollution from many sources (Ouedraogo et al., 2019). This has driven the need to examine the sensitivity of groundwater to surface pollutants, referred to as the *groundwater vulnerability* (National_Research_Council, 1993). Existing methods of groundwater vulnerability assessment (GVA) can be categorised into four groups: (i) overlay and index-based methods, (ii) process-based simulation models, (iii) statistical methods, and (iv) hybrid methods (Aslam et al., 2018). In overlay and index-based methods, numerical scores are assigned to different hydrological and geological parameters and applied to an aquifer to assess its vulnerability. Despite their subjectivity in the choices of parameters and indices, with different standards adopted in different countries, these are the most common methods for GVA. In process-based methods, flow- and mass transport models are used to calculate the vulnerability for a specific aquifer. While these can be very accurate, they are generally limited to small regions with abundant geological data. A variety of statistical methods have also been applied, including orthodox statistical tools, data-driven methods and Bayesian inference, while hybrid methods involve a synthesis of several methods. Bayesian inference offers many advantages for GVA, in that it directly calculates the probability that pollutants will reach the water table, and also enables the synthesis of theory and data by the method of Bayesian updating (Fu et al., 2020). However, there have been few applications of Bayesian inference to GVA.

In this study, we apply Bayesian inference to assess the vulnerability of groundwater in the Burdekin Basin, Queensland, Australia, to nitrate pollution. The connection between reported nitrate concentrations and different hydrological and geological parameters is first represented by the correlation:

$$\mathbf{C}(\mathbf{x}) = \boldsymbol{\Theta}(\mathbf{x})\Xi(\mathbf{x}) + \boldsymbol{\epsilon}(\mathbf{x}) \tag{1}$$

where $\mathbf{C}$ is a matrix of nitrate concentrations, $\boldsymbol{\Theta}$ is a matrix of parameters, Ξ is a vector of indices and $\boldsymbol{\epsilon}$ is a noise matrix, in general written as a time-series for each position $\mathbf{x}$. This is expressed by Bayes' rule as $p(\Xi|\mathbf{C}) \propto p(\mathbf{C}|\Xi)\, p(\Xi)$. Applying the maximum a posteriori (MAP) Bayesian method by maximising $p(\Xi|\mathbf{C})$, assuming Gaussian noise and likelihood functions for each parameter, the coefficient matrix Ξ can be calculated by a Bayesian sparse regression, involving minimisation of the objective function:

$$J(\Xi) = ||\mathbf{C} - \boldsymbol{\Theta}\Xi||_2^2 + \lambda||\Xi||_2^2 \tag{2}$$

where $||\,||_2$ is the Euclidian norm, and λ is a regularisation parameter that can be extracted from the noise and likelihood functions. The analysis is conducted using point nitrate data within a GIS framework, enabling the computation of a groundwater vulnerability map for the Burdekin Basin. This is compared to maps derived using the DRASTIC index-based method (Aller et al., 1985). The Bayesian method bears many similarities to the overlay and index-based methods, in that it is based on a correlation using indexed parameters, but chooses the set of relevant parameters and assigns their indices using a rigorous mathematical framework. The results demonstrate that the DRASTIC method does not correctly account for the functional dependence of known vulnerabilities.

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Keywords: *Groundwater vulnerability assessment, Bayesian inference, DRASTIC, GIS*

EXTENDED ABSTRACT ONLY

Comparison of Darcy's law and Brinkman equation on saltwater intrusion simulations

Jingwei Yao [a] **and Hong Zhang** [a]

[a] *School of Engineering and Built Environment, Griffith University, Gold Coast, 4215, Australia*
Email: jingwei.yao@griffithuni.edu.au

Abstract: Coastal areas have been widely threatened by the global expansion of seawater intrusion with the anthropogenic activities and climate change. A thorough understanding and accurate prediction of the process is required for a sustainable management of the fresh groundwater resources. The exchange between inland groundwater and the ocean has been investigated over the last six decades and achievements have been made to optimise the accuracy of numerical solutions. But most recently, the limitations of traditional hydrodynamic models appear especially for transition flows in the vicinity of surface water bodies (Mirzavand et al., 2020).

Classical seawater intrusion models apply Darcy's law as the governing equation, which describes the linear relationship between the pressure gradient and groundwater flux. One of the limitations of Darcy's law is that it neglects the viscous force acting on a moving fluid considering the porous media constrains the flow velocity at a low level. Thus, Darcy' law is only valid for slow-moving groundwater, practically with Reynolds number smaller than one. Brinkman (1949) introduced an extension to the traditional Darcy's law which included a viscosity term to account for the dissipation of the kinetic energy by viscous stress. In this way, the Brinkman equation provides a more general description for subsurface flow. For seawater intrusion problems, it is necessary to discover under what conditions Darcy's law is invalid and Brinkman equation can produce more accurate results.

In this study, numerical simulations of saltwater intrusion were conducted with COMSOL Multiphysics, which can solve for groundwater flow and dispersive solute transport by mass and momentum conservations. Modules using Darcy' law and Brinkman equation are both applicable in COMSOL. An analytical solution of Henry's problem was employed to verify the numerical technique as a benchmarking of the COMSOL codes. The numerical model simulated a vertical section of the coastal aquifer with one side exposed to a saltwater body. On the inland side, the boundary either used a constant head or freshwater influx. On the seaside was a constant head boundary with tidal fluctuations. The hydraulic head and density difference drive the salt entering the aquifer from seaside. The impacts of head differences, tidal amplitudes, hydraulic conductivities and porosities of the porous media were investigated.

Simulation results indicate that outcomes from the two models highly respond to each other when Reynolds number is small. However, discrepancy increase with the increase of Reynolds number. The effect of viscous shear intensifies with Reynolds number; thus Darcy's law tends to overestimate the flow velocity. The propagation of the saltwater-freshwater interface is also faster for Darcy's law. When applying a head difference of 3 m and tidal amplitude of 1.5 m, the Reynolds number reaches 0.0025. The Darcy's velocity is twice that of Brinkman's and it takes 80 more days for Brinkman model to reach a steady state than Darcy's. Therefore, Darcy's law can be used for low-Reynolds number flow while Brinkman equation is more accurate when it comes to high Reynolds number flow. Noted that this accuracy is compensated by longer computational time. In seawater intrusion studies, Brinkman equation can provide a more accurate description of groundwater flow especially in high permeability areas including the transition areas close to surface water bodies and pumping wells, which facilitates a better freshwater resources and salt management in coastal zones.

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Keywords: *Darcy's law, Brinkman equation, seawater intrusion, numerical simulation*

EXTENDED ABSTRACT ONLY

Combining palaeoclimate data and stochastic modelling to improve water security

Matthew S. Armstrong[a], **Anthony S. Kiem**[a], **George Kuczera**[b], **Tessa R. Vance**[c], **and Kathryn J. Allen**[d]

[a]Centre for Water, Climate and Land (CWCL), University of Newcastle, Callaghan, 2308, NSW, Australia [b]School of Engineering, University of Newcastle, Callaghan, NSW 2308, Australia
[c]Australian Antarctic Program Partnership, Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, Tasmania 7004, Australia
[d]School of Geography, Planning and Spatial Sciences, University of Tasmania, Hobart, Tasmania 7004, Australia
Email: matthew.armstrong@uon.edu.au

Abstract: Remote hydroclimatic proxies (e.g., ice cores) contain useful information about regional hydroclimatic persistence. However, the low skill of these records in predicting local rainfall/streamflow magnitudes limits their immediate usefulness to water management. In this study, we present a Bayesian Hierarchical framework whereby proxy rainfall data from the Law Dome ice core (located in coastal East Antarctica to the south of Australia, record length of 1,013 years) is used to inform the calibration of a stochastic rainfall model for the Williams River catchment (located in southeast Australia, with a record length of 120 years). These two regions are linked via synoptic to seasonal scale modulations of meridional circulation and atmospheric moisture patterns in the southern Indian Ocean south of Australia that drive respective regional hydroclimatic variability. The proposed stochastic framework assumes that Autoregressive Moving Average (ARMA(1,1)) model (Box *et al.*, 1970) persistence parameters (which are able to reproduce Law Dome low-frequency climate variability) for the proxy and rainfall time series come from the same posterior distribution, but identifies mean and standard deviation posteriors separately for each time series. The palaeoclimate-informed ARMA(1,1) model reproduces observed rainfall coefficient of variation but, compared with an ARMA(1,1) model calibrated using only observed rainfall data, also simulates much longer and more severe droughts/pluvials. When using the palaeoclimate-informed ARMA(1,1) model outputs to calculate reservoir inflow and required reservoir storage, these extended droughts/pluvials result in storage distributions with much larger medians and variances than what stochastic modelling using just the instrumental record suggests is required. This study (a) highlights limitations with using only instrumental data to characterise climate risk and (b) presents a novel framework in which low-frequency variability contained in palaeoclimate proxy records can be incorporated in stochastic modelling/water management.

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Keywords: *Paleoclimate, water management, Bayesian hierarchical model*

Assessing uncertainty in large-scale hydrological and sediment modelling using nested domains under current and changing climate

Alena Bartosova[a], Berit Arheimer[a], Alban de Lavenne[a,b], René Capell[a] and Johan Strömqvist[a]

[a] *SMHI / Swedish Meteorological and Hydrological Institute, Folkborgsvägen 17, 601 76 Norrköping, Sweden*
[b] *Université Paris-Saclay, INRAE, UR HYCAR, 1 Rue Pierre-Gilles de Gennes, 92160 Antony, France*
Email: alena.bartosova@smhi.se

Abstract: Continental and global dynamic hydrological models have emerged recently as tools for e.g. flood forecasting, large-scale climate impact analyses, and estimation of time-dynamic water fluxes into sea basins. One such tool is a dynamic process-based rainfall-runoff and water quality model, Hydrological Predictions for Environment (HYPE, see https://hypeweb.smhi.se/). We present and compare historical simulations of runoff, soil moisture, aridity, and sediment concentrations for three nested model domains using global (WWH), continental (Europe, E-HYPE), and national (Sweden, S-HYPE) catchment-based HYPE applications (Table 1). Future impacts on hydrological variables from changing climate were then assessed using the global and continental HYPE applications with ensembles based on three Coupled Model Intercomparison Project Phase 5 global climate models (GCMs). We illustrate how modeling across nested domains enables additional assessments of uncertainty, both in terms of projected impacts and modelling setups, and highlight how various model performance criteria play different roles in model calibration.

Table 1. Comparison of WW-HYPE, E-HYPE, and S-HYPE (adapted from Bartosova et al., 2021)

Metric	WWH	E-HYPE	S-HYPE
Average catchment size (km^2)	1 000	200	7
Number of flow gaging sites per million km^2	85	26	1 066
Median NSE/KGE for discharge	0.16/0.40	0.44/0.56	0.74/0.83
Number of sediment monitoring sites per million km^2	6.5	37	171
% sites within 25%/50% RE for sediment	25/47	24/47	36/70
Corr. coeff. for sediment at global/European/Swedish domains	0.30/0.06/-0.13	-/0.37/0.31	-/-/0.72

After accounting for the spatial resolution, simulated historical runoff values were quite similar among the nested models while sediment concentrations varied considerably in spatial patterns. Regardless of the variation, the global model was able to provide information on climate change impacts comparable to those from the continental and national models for hydrological indicators. Output variables that were calibrated, e.g. runoff, were shown to result in more reliable and consistent projected changes among the different model scales than derived variables such as the actual aridity index. The comparison was carried out for ensemble averages as well as individual GCMs to illustrate the variability and the need for robust assessments.

Global hydrological models are shown to be valuable tools for e.g. first screenings of climate change effects and detection of spatial patterns and can be useful to provide information on current and future hydrological states at various domains. The challenges are (1) in deciding when we should use the large-scale models and (2) in interpreting the results, considering the uncertainty of the model results and quality of data especially at the global scale. Comparison across nested domains demonstrates the significance of scale, which needs to be considered when interpreting the impacts alongside with model performance, and supports the need to use model ensembles for large-scale analyses instead of a single model.

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Keywords: *Large scale hydrological model, suspended sediment, climate change, model scale*

An Assessment of economic and environmental benefits of desilting village tanks in Sri Lanka: An application of linear programming

D. Dayananda[a], W.A.D.S. Dilhari[b] and J. Weerahewa [b c]

[a]Postgraduate Institute of Agriculture, University of Peradeniya, Sri Lanka, [b]Department of Agricultural Economics and Business Management, Faculty of Agriculture, University of Peradeniya, [c]School of Food and Agriculture, University of Melbourne, Australia.
E mail: dasuni447@gmail.com

Abstract: Village tanks are climate smart irrigation infrastructures predominant in the Dry Zone of Sri Lanka from ancient times. They have degraded over time, and the rehabilitation of tanks has become a dire need of the society. Out of the many rehabilitation approaches, the removal of silt, commonly known as desiltation, has been the most widely used approach. Desiltation increases the availability of irrigation water by increasing storage capacity of the tanks. In addition to increasing irrigation potential, desilting has many positive impacts in terms of ecosystem benefits. The objective of this paper is to assess the returns on investments of desiltation of village tanks in Sri Lanka's Dry Zone. The study employs a cost-benefit analysis to compare the cost of alternative desiltation scenarios with the economic and environmental benefits of desiltation of three village tanks in *Mahakanumulla* village in Anuradhapura District. A Linear Programming (LP) model was developed and simulated to assess the profitability of crop cultivation under tank desiltation with and without market interventions. The benefits of regulating, supporting and cultural services were assessed under various hypothetical scenarios. The simulation results of the LP model indicate that desiltation does not bring in significant benefits if market interventions are not present. The rates of returns to investments are higher with a 25% desiltation compared to that of 50%, implying that the degree of desiltation also matters. Furthermore, the findings reveal that when values of multiple eco-system services are accounted, desiltation strategies bring in positive returns. Partial desiltation along with market interventions are recommended to cover the cost of investments on minor tank rehabilitation.

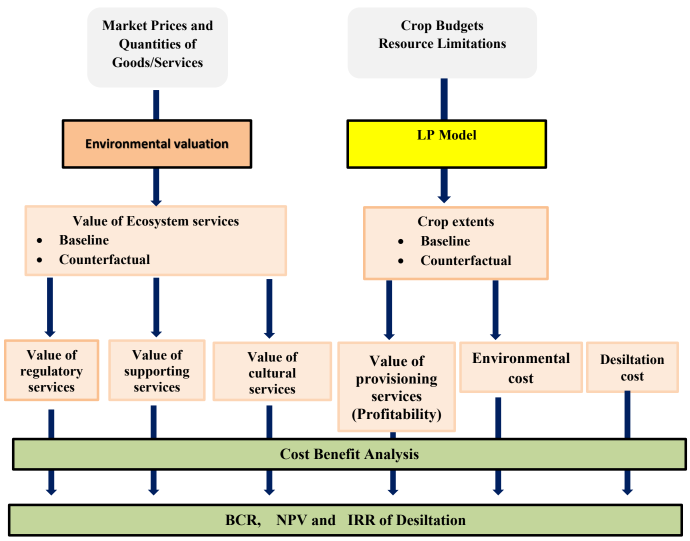

Figure 1. Approach for assessing economic and environmental benefits of desilting village tanks

Keywords: *Desiltation, linear programming model, cost-benefit analysis, ecosystem benefits*

Adaptation of transboundary water management in the Amu Darya Basin to possible climate changes

Weili Duan [a, b], **Yaning Chen** [a, b] **and Shan Zou** [a, b, c]

[a] *State Key Laboratory of Desert and Oasis Ecology, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi, 830011 China*
[b] *University of Chinese Academy of Sciences, Beijing 10049, China*
[c] *Department of Geography, Ghent University, Ghent 9000, Belgium*
Email: duanweili@ms.xib.ac.cn(Weili Duan); chenyn@ms.xjb.ac.cn(Yaning Chen); zoushan17@mails.ucas.ac.cn (Shan Zou)

Abstract: Water is critical for socio-economic sustainable development, food and energy production, healthy ecosystems resources and is also at core of adaption to changing climate. The water security is uniquely vulnerable in Central Asia, a region replete with transboundary water conflicts, shortages in land and water resources and high sensitivity to climate change.

The ongoing population growth and climate variability exacerbate water stress in Central Asia (Jalilov et al., 2016). Among these transboundary rivers in Central Asia, Amu Darya River is the largest river and shared by Afghanistan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan. Its water used mainly for agriculture, hydropower generation, industrial, domestic, and drinking purposes, and has been considered as the most important limiting factor for socio-economic development among riparian countries. In order to defuse the tension, regional integration and collaboration in the Amu Darya River Basin is needed urgently to promote a more efficient use of water for food and energy production and to address ecological environment problems related to the overuse of water resources (Cai et al., 2003; Duan et al., 2019; Rakhmatullaev et al., 2010).

Using a water balance approach for the Amu Darya River Basin, we present a synthetic evaluation of future water use, crop yields, and land and water productivities for the period 2016 to 2055 in 13 provinces in Tajikistan, Turkmenistan, and Uzbekistan. Modelled future socio-economic scenarios include food security and diet change (FSD), export-oriented sustainable adaptation (ESA) and business as usual (BAU). Results show that a slight increasing trend was detected in runoff of Amu Darya River from 2016 to 2055, with the Mann-Kendall Z value (Hamed and Rao, 1998) at 0.90, the average of which is about 68.45 km^3/year, a decrease at 0.45 km^3/year compared with that over 1932-2015. Predictions of future annual total water withdrawal in 13 main planning zones (3 in Tajikistan, 6 in Uzbekistan, and 4 in Turkmenistan) vary substantially with the coefficient (50%, 75%, and 100%) of water availability in transboundary sources and three future socio-economic scenarios (BAU, FSD, and ESA) and most of them declines significantly ($p<0.05$) from 2016 to 2055.

Generally, results obtained from this study could offer insights to help water resources managers to identify vulnerabilities in the water resources security and sustainable development.

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Keywords: *Water resources, socio-economic scenarios, Amu Darya Basin, Central Asia*

Changes in flooding in highly glacierized catchments in the Tarim River Basin

Gonghuan Fang [a], Zhi Li [a#], Jing Yang [b], Yaning Chen [a], Charles Amory [c,d], Weili Duan [a] and Yunqian Wang [e]

[a] *State Key Laboratory of Desert and Oasis Ecology, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, China (G. Fang: fanggh@ms.xjb.ac.cn; Z. Li: liz@ms.xjb.ac.cn; Y. Chen: chenyn@ms.xjb.ac.cn; W. Duan: duanweili@ms.xjb.ac.cn)*
[b] *National Institute of Water and Atmospheric Research, Christchurch 8000, New Zealand (J. Yang: jing.yang@niwa.co.nz)*
[c] *Department of Geography, University of Liège, Liège 4000, Belgium*
[d] *Université Grenoble Alpes, CNRS, Institut des Géosciences de l'Environnement, Grenoble 38100, France (C. Amory: charles.amory@univ-grenoble-alpes.fr)*
[e] *School of Geography and Tourism, Qufu Normal University, Rizhao 276826, China (Y. Wang: wangyq@qfnu.edu.cn)*

Abstract: Flooding is one of the most dangerous and affecting climate-related disasters, and climate change alters the intensity and frequency of floods worldwide. Many studies have analyzed historical trends in annual peak flow and shown that the trend magnitude and direction vary strongly by region. With global warming, mountain systems are particularly sensitive to climate change because of climate amplification by feedback associated with high-elevation snow cover, albedo, and water-heat budget and the complex river recharge processes.

This study examined long-term changes in flood characteristics (including magnitude, frequency and timing) in 30 typical alpine headwaters in the large endorheic Tarim River Basin, central Asia. The contributions of climatic factors to flood changes were investigated using numerical experiments and random forest approach.

The results indicate that: (1) annual maximum flood peaks in the area increased at most stations during 1960-2015, with increased flood frequency. Earlier flood peaks were observed in spring, advancing at a rate of 1.38 day/10a, while for other seasons, changes in the occurrence time of flood peaks showed strong spatial variability; (2) In these alpine catchments, catchment characteristics such as runoff coefficient, runoff depth, catchment area, and channel slope had a significant impact on flood magnitude, while average elevation, glacierization, and channel slope affected flood timing; (3) Although precipitation was the dominant factor for the increased flood magnitude in most catchments of the southern slope of the Tianshan Mountains, temperature played a greater role in the northern Kunlun Mountains. For flood timing changes, melt level height and precipitation were the most influential factors in the alpine catchments in Central Asia.

The results of this study provide information on the spatiotemporal variations of floods and their driving factors in this alpine basin, which could be used in effective local water resource management against climate change.

Keywords: *Floods, attribution analysis, random forest, numerical experiments, glacierized catchments*

An inclusive city water account by integrating multiple data sources for South-East Queensland (SEQ), Australia

K M Nazmul Islam [a,b,e], **Steven J. Kenway**[b], **Marguerite A. Renouf** [c], and **Thomas Wiedmann** [d]

[a] School of Chemical Engineering, University of Queensland, QLD, 4072, Australia, [b] Australian Centre for Water and Environmental Biotechnology (formerly AWMC), University of Queensland, QLD, 4072, Australia, [c] QUT Centre for Agriculture and the Bioeconomy (CAB), Queensland University of Technology, QLD, 4000, Australia, [d] Sustainability Assessment Program (SAP), School of Civil and Environmental Engineering, UNSW, Sydney NSW 2052, Australia, [e] Institute of Forestry and Environmental Sciences, University of Chittagong, Chittagong 4331, Bangladesh
Email: kmnazmul.islam@uq.net.au

Abstract: Cities are the hotspots of impacts on local and distant water resources through economic activity and consumption. More than half of the world's population lives in cities, which is expected to reach around two-thirds by 2050. Such a high level of increased urbanization calls for higher attention towards inclusive, safe, resilient, and sustainable cities (Sustainable Development Goals 11). To evaluate sustainability, inclusiveness, and resiliency pathways, a variety of sustainability indicators have been proposed, including the water footprint. The water footprint is defined as the total volume of freshwater used for the goods and services consumed. It covers both direct (e.g. drinking and cleaning) and virtual water flows (water used in the goods and services supply chain, hence also known as embedded water).

Virtual water flows through products and services produced in other locations using their water resources influence the function, prosperity, and growth of the cities. Yet, this aspect is absent in the sustainability and strategic city water footprint reduction goals of Australian cities. To fully account for the water dependencies of Australian cities, direct and virtual water flows need to be known. To this purpose, we build inclusive city water of South-East Queensland (SEQ) by combining material flow analysis (MFA) and the multiregional input-output (MRIO) model. Water consumption in SEQ is used to quantify the water footprint on local water resources and net blue virtual water import. Together, this constitutes the water footprint on national water resources. Our results show that the water footprint of SEQ on local water resources is 620 GL with a net virtual water import of 1382 GL. Therefore, the water footprint of SEQ on national water resources is 2002 GL. The water footprint of SEQ on local water resources consists of direct water consumption by households (192 GL) and the industrial sector (428 GL). The consumed direct water of the SEQ industrial sector flows as virtual water to SEQ (149 GL), the rest of Australia (RoAUS) (all other regions except SEQ) (211 GL), and the rest of the world (68 GL). The virtual water inflows breakdown by source regions showed that 386 GL, 1019 GL, and 256 GL of virtual water imported from the major cities (Sydney, Melbourne, Adelaide, and Perth); regional areas of NSW, Victoria, and QLD; and RoAUS, respectively. Overall, the proposed inclusive city water account can enhance subnational estimates of city water footprint for benchmarking, as well as inclusive and resilient city water planning.

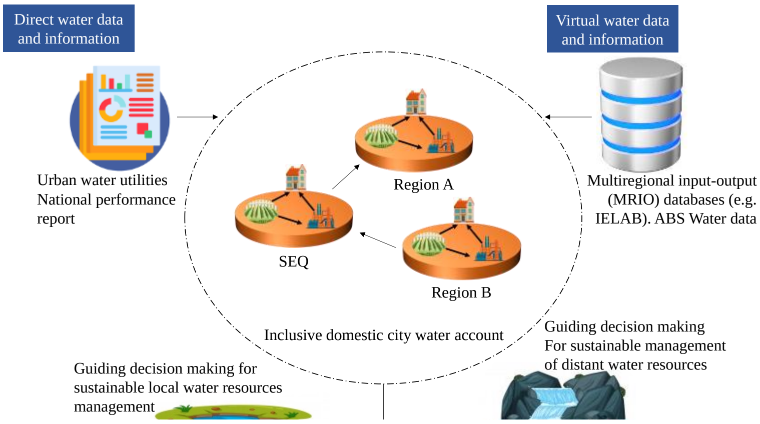

Figure 1. Conceptual figure of an inclusive city account for driving strong sustainability action in Australia cities.

Keywords: *Water footprint, urban metabolism, integrated city water account*

Evaluation of the time of concentration estimation methods for small rural watersheds

Bruna Nogueira Rezende [a], **Vassiliki T. G. Boulomytis** [a,b,c], **Sérgio Nascimento Duarte** [a], **Marco Antonio Jacomazzi** [c] **and Antônio Carlos Zuffo** [c]

[a] University of Sao Paulo (USP), College of Agriculture "Luiz de Queiroz"- ESALQ, Department of Biosystems Engineering, Piracicaba, SP, Brazil [b] Federal Institute of Science, Education and Technology of Sao Paulo - IFSP, Faculty of Civil Engineering, Caraguatatuba, SP, Brazil [c] State University of Campinas – UNICAMP, School of Civil Engineering, Architecture and Urban Design, Campinas, SP, Brazil
Email: bruna.n.rezende@usp.br

Abstract: The time of concentration (tc) is a widely used input parameter for the design of hydrographs, peak flow estimates, and runoff hydrological models. Conceptually, it is the average time it takes for water to flow from the most hydrologically distant location of the watershed to its outlet. The tc varies according to the characteristics of the basin, such as average slope, length and soil infiltration. It can be evaluated by calculating the time elapsed between the moment the effective rain stops and the end of the runoff identified by the hydrograph infusion point. When calculating the tc, there are some uncertainties that affect the performance of tc acquisition methods. The tc observations can generally be overestimated if they refer to runoff with a low hydraulic load. Because of that, the regular and effective assessment of watersheds is commonly used to validate the most appropriate tc estimation method. Among the equations used to estimate the tc of a watershed, this study aims to evaluate and compare the performance of twelve empirical and semi-empirical methods in three small rural watersheds in the state of São Paulo, Brazil. All watersheds had smaller areas than 81 km² and none of them are assessed. The tc estimates of the different models ranged between 1.08 h and 15.19 h, 1.00 h and 17.23 h, and 0.80 h and 8.20 h for the Barreiro, Copaiba and Lambari watersheds, respectively. The lowest tc value was estimated by the DNOS method and the longest one by the SCS Lag method for the Barreiro and Lambari watersheds. For Copaiba watershed, the lowest tc value was estimated by the DNOS method as well, but the highest tc value was derived by the Venturi equation. The tc estimates for the Lambari watershed were about twice higher than those of Copaiba watershed, although their areas were approximately similar. This difference among the estimates was strongly influenced by the explanatory variable of the thalweg models, followed by the mean slope. The results revealed that among the analysed formulas, the DNOS, Kirpich and Picking methods showed great similarity for presenting the smallest tc, causing the design of larger control structures. The SCS Lag and the Kinematic Wave method presented the highest tc, which can lead to lack of safety in hydraulic structures.

Keywords: *Rural watersheds, time of concentration, uncertainty, land use and land cover*

University and Water Authority Collaboration in the Sardinia Water Plan: The role of generic simulation models

Andrea Sulis [a], Paolo Botti [b], Mariano Pintus [b], Adriano Ruiu [c], Luigi Zucca [c], Riccardo Zucca [c] and Giovanni M. Sechi [c]

[a] *Dept. of Architecture, Design and Urban planning (DADU), University of Sassari*
[b] *Autorità di Distretto Idrografico Sardegna (ADIS)*
[c] *Dept. of Civil and Environmental Engineering (DICAAR), University of Cagliari*
Email: asulis@uniss.it

Abstract: The paper presents the goals, methodologies and products of a large scientific collaboration between the Department of Civil and Environmental Engineering (DICAAR) at the University of Cagliari (Italy) and the Sardinia Water Authority (ADIS-Italy). The collaboration started in 2016 and the activities will be completed at the end of 2022. The main goal has included the identification and evaluation of alternative infrastructural and non-structural measures that may increase the available water supplies and hydropower production, improve flood protection and enhance water quality in the region. Quantitative system performance criteria have been defined and applied to identify management policies (reservoir and allocation rules) and to help select infrastructural alternatives in a complex multi-reservoir water system under different time horizons. This integrated, multipurpose "master development plan" (Loucks and van Beek, 2017) has mostly been created in a top-down approach while the interested stakeholders, potentially affected by the measures being considered, will actively participate in a subsequent phase of consensus building.

The large amount of available data has been used in a generic simulation model (WARGI-SIM) to predict the interaction and impacts, over time and space, of considered measures. This kind of models has been, and will be, centrale to the planning and manage the decision process. Specifically, generic simulation models provide an efficient way to predict source-demand interactions in order to identify a set of measures that provide the higher performance criteria values. A large variety of generic simulation models within interactive graphics-based interfaces has been developed by public and private organizations (e.g., AQUATOOL, MODSIM, WEAP, RIBASIM, WARGI-SIM) (Sulis and Sechi, 2013). Many are models where optimization methods are developed on the single time period and results are used as an efficient mechanism for performing simulations. WARGI-SIM (Sechi and Sulis, 2009) is a simulation-only model based on a more conventional, but decision-process adherent, "if-then" approach. This approach uses supply preferences and demand priorities defined by the user to implement the system management policies.

Simulation results are summarized in terms of reliability, resilience and vulnerability (RRV) performance indexes where the satisfactory states are defined based on assigned thresholds of water supply, ecological flow, reservoirs level and hydropower generation values. When system performance criteria are in conflict, WARGI-SIM can help to identify efficient trade-offs in a RRV hierarchy approach using a frequency analysis of WARGI simulation results in a 1000-years simulation length. By comparison of different infrastructural and non-structural scenarios, the results show the percentages of water demand that could be assured to different users with a selected probability and how the agriculture sector can benefit from an early warning application of this demand reduction measure.

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Keywords: *Complex water system, system policy, generic simulation model, WARGI-SIM, RRV analysis*

Modelling and prediction of turbidity in water

Parul Tiwari[a], Don Kulasiri[a] and Sandhya Samarasinghe[b]

[a] Centre for Advanced Computational Solutions, Lincoln University, New Zealand;
[b]Complex Systems Big data and Informatics Initiative (CSBII), Lincoln University, New Zealand
Email: parultiwari8922@gmail.com

Abstract: Clean water is vital to our health. For effective water quality management, fast and efficient alternative methods such as artificial intelligence (AI) models are needed. In this analysis, New Zealand (NZ) river water data (https://shiny.niwa.co.nz/nzrivermaps) is used. Spatial modelling of this dataset is done by the authors in (Whitehead, A, 2018). In current analysis, a knowledge driven machine learning based computational model for predicting turbidity measures is developed using Different machine learning (ML) Regressors such as Decision Tree (DTR), Support Vector (SVR), Random Forest (RFR) and Gradient Boosting (GBR). These algorithms are assessed and compared based on their performance metrics: Mean absolute error (MAE), Root Mean Square Error (RMSE) and coefficient of determination (Table1). Pipeline of the machine learning model is shown in Figure 1.

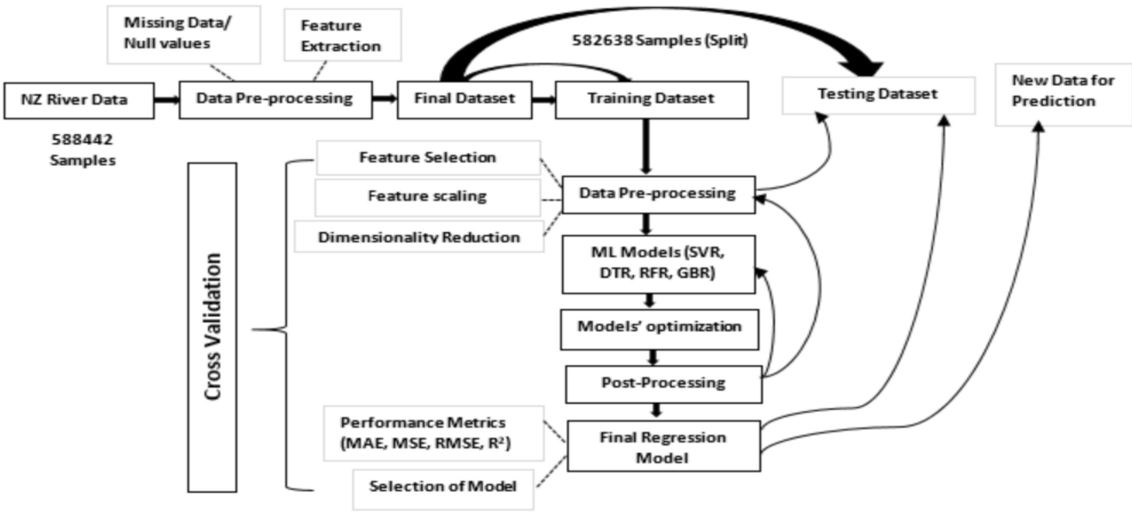

Figure 1. Workflow Diagram of Machine Learning Model

Based on these metrics RFR and DTR performs marginally better as compared to SVR. GBR is not too far behind these two models. However, the applicability of these methods depends on the choice and response of different kernel functions in predictive models. Unlike traditional regression methods, the machine learning approach applies different probabilistic and optimization techniques in learning regularities and patterns in data, establishing complex nonlinear relationships between noisy and interdependent variables. With the help of this study, it is possible to make inferences and decisions that are difficult to make using conventional statistical methodologies resulting in improved efficiencies of the system. One can accurately predict the turbidity in water for new set of data using RFR or DTR or both ML models. This study will assist the decision makers to test the water quality of an unknown location by using turbidity measure as an input in ML model.

Table1. Performance metrics for different machine learning models

Performance Metrics	Machine Learning Models			
	DTR	SVR	RFR	GBR
MAE	9.590e-05	0.35877	5.682e-05	0.00507
RMSE	0.00324	0.82716	0.005869	0.00847
R^2-score	0.9999	0.84235	0.9999655	0.99992

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Keywords: *Machine learning, turbidity in water*

Reducing bias and improving accuracy of velocity index in tidal rivers using CEEMDAN filtered time series HADCP velocity

Stephen Wallace[a]

[a]*Department of Resources, Rockhampton, Qld, Australia*
Email: stephen.wallace@resources.qld.gov.au

Abstract: In tidally affected rivers, horizontal acoustic Doppler current profilers (HADCP) are essential for discharge calculation, by measuring velocity and multiplying by cross sectional area. It is simple and safe to gauge an estuary during tidal conditions to develop a velocity index (VI) relationship, as tidal gaugings can be done on any high tide without waiting for a high flow event. However, it would be erroneous to assume that the VI that applies during tidal conditions can be equally applied to the same section of river during flood events.

The standard method for developing a VI for an open channel uses HADCP raw velocity (*Xvel*) and water level (*Ht*) as factors and therefore does not consider a difference between tide and event conditions. An improved method of velocity indexing specifically for tidal rivers is presented to determine if considering tide and event components separately improves regression fit and reduces bias when compared to the standard VI method.

A side-looking Channelmaster HADCP (300kHz) was installed at a tidal site on the Johnstone River at Innisfail, Queensland. The site was gauged frequently during tidal conditions from 2016 to 2019 and gauged during a moderate flood in 2021. To differentiate between tide and event components, time series *Xvel* was decomposed into intrinsic mode functions (IMF), using Complete Ensemble Empirical Mode Decomposition with Adaptive Noise (CEEMDAN). Empirical mode decomposition (EMD) is useful for non-linear, non-stationary signals (Huang et al 1998), such as tidal river flows. Each IMF has a dominant time frequency (f) in hours, which represent semidiurnal (D_1), diurnal (D_2) and event (E) components. D_1 is the sum of $\mathrm{IMF}_{f<16}$, D_2 was the sum of $\mathrm{IMF}_{16<=f<25}$, E was the sum of $\mathrm{IMF}_{f>=25}$. Gauged velocities were regressed against D_1, D_2, E, and $E*Ht$ (CEEMDAN VI) during tidal and event conditions, and the coefficients were used for the VI equation.

Comparing all gauged flows to calculated flows using CEEMDAN VI compared to the standard VI method improved model fit (mean-square error 83.3m^3/s and 113.3m^3/s, R^2 0.96 and 0.92, respectively). The CEEMDAN VI method was also an improvement over the standard VI method at predicting the full set of gaugings when velocity indexed with a subset of event-only gaugings (mean-square error 86.5m^3/s and 130.3m^3/s, R^2 0.96 and 0.92, respectively). Bias was reduced in CEEMDAN VI over the standard VI method with a slope of 0.98 versus 0.92, respectively.

The improved model fit and reduction in model bias using CEEMDAN VI supports the hypothesis that there is a difference in tide and event velocity indexes, and CEEMDAN for decomposing the velocities is an appropriate method of separating tidal and event components for time series velocity. Using CEEMDAN VI avoids assuming that a simple velocity index can be extrapolated across a range of flows. This paper only explored one method of separating the tidal and event components, however other methods could be explored. Similar sites are operated across the Great Barrier Reef catchments, and the same method is applied successfully.

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Keywords: *Hydrology, empirical mode decomposition, HADCP, velocity index, tidal*

Metamodelling "naturalised" groundwater levels across Greater Wellington region in New Zealand for groundwater management

J. Yang [a], **D. Booker** [a], **C. Rajanayaka** [a], **C. Daughney** [a], **R. Morris** [b] **and M. Thompson** [b]

[a] *National Institute of Water & Atmospheric Research, New Zealand*
[b] *Greater Wellington Regional Council, New Zealand*
Email: jing.yang@niwa.co.nz

Abstract: Like many parts in the world, groundwater is an important resource for the Greater Wellington region in New Zealand and is a major source of water supply for municipalities, rural communities, industries and farms. Greater Wellington Regional Council (GWRC), which is responsible for managing water resources in the region, requires an understanding of naturalised groundwater levels for sustainable groundwater management and to fulfil national regulatory requirements such as state of the environment reporting and limit setting for resource use. However, as the groundwater systems have been significantly altered by humans through water extractions, the available measured groundwater level data do not represent natural groundwater levels. Whilst GWRC has previously used physical-based modelling approaches (e.g. FEFLOW; Diersch 2014) for estimating naturalised groundwater levels, in recent years data and information hungry processes such as plan changes have encouraged GWRC to consider innovative alternatives to support faster decision-making. To this end, we have developed a stepwise linear regression model that emulates the functionality of previously applied physical-based models across the region without re-calibration of physical-based models. The model inputs include local weather data (i.e., precipitation and temperature, representing the local weather system influencing local groundwater recharge), and nearby river flow (representing the upstream weather system). The model was trained against the available historical naturalised groundwater level time series that were previously developed using GWRC's physical-based models for the period of 1992 to 2007. To test the validity of this statistical method in the Ruamahanga Plains, three groundwater borehole sites were chosen in the upper valley, middle valley and lower valley with three different hydrological-hydrogeological settings: (1) shallow aquifer and close to the river, (2) shallow aquifer and far from the river, and (3) confined aquifer and far from the river. Cross validation was used to assess the ability of the statistical model to independently predict weekly groundwater levels. Coefficient of determination (R^2) and Nash-Sutcliffe Efficiency (NSE) at each borehole site were used as performance metrics. Results demonstrate satisfactory model performance with R^2 of 0.73, 0.63 and 0.95, and NSE of 0.72, 0.61 and 0.95, for these three borehole sites. Results indicated that the statistical modelling method is a robust approach to estimate naturalised groundwater levels and sufficient to inform decision making. We are therefore applying this method to the entire Greater Wellington region to generate predictions of naturalised groundwater levels for the period of 2008 to 2020.

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Keywords: *Naturalised groundwater level, metamodelling, regional groundwater system, groundwater management, New Zealand*

Uncertainty analysis of moisture content modelling due to variability in physical and hydraulic soil properties

Qazi Muqeet Amir[a], Chiara Pasut[a,b] and Federico Maggi[a]

[a] Laboratory for Advanced Environmental Engineering Research, School of Civil Engineering, The University of Sydney, Bld. J05, 2006 Sydney, NSW, Australia, [b] Sydney Institute of Agriculture, School of Life and Environmental Sciences, The University of Sydney, New South Wales, Australia

Email: muqeet.amir@sydney.edu.au, c.pasut@sydney.edu.au, federico.maggi@sydney.edu.au

Abstract: Ground water is the world's largest accessible source of fresh water, with over 2 billion people relying on it as their primary water supply (Alley et al., 2002). Global and regional scale modelling assessments are useful tools to gain deeper insight into soil water dynamics. However, with soil physical and hydraulic properties varying significantly at a regional scale, understanding the variability in soil moisture content and subsequently, groundwater recharge, is vital to improve the accuracy of groundwater models.

The aim of this project is to quantify the uncertainty in the volumetric soil moisture content (θ), with varying physical and hydraulic soil parameters in Australia and New Zealand. These soil properties include porosity (ϕ), permeability (K), pore volume distribution index (b), liquid residual saturation (S_r), and matric potential of the Brooks and Corey Model (ψ_s) One hundred stochastic Monte Carlo simulations of 10% of the grid cells within this domain were conducted using the BRTSim computational solver, at 0.25x0.25degree resolution (about 30 km x 30 km at the equator) over 45 years, from 1970 to 2014. Values of the soil properties were randomly extracted between +/- 20% of the values used in our earlier study (Guglielmo et al., 2021), which used a deterministic approach. After conducting the Monte Carlo simulations, θ in the remaining 90% of grid cells was reconstructed by a linear interpolation using the average of the neighboring grid cells weighted by distance. We compared the average of the stochastic θ from 2005 to 2014 to the average θ of the deterministic simulations in Guglielmo et al., (2021) across the same time period to calculate the anomaly. We found that the anomaly in θ ranged between +/-0.2 and that 90.7% of grid cells varied between +/-0.05 (Figure 1a). The anomaly in θ shows no pattern, with most grid cells showing the stochastic moisture content to be within +/- 0.05 of the deterministic moisture content.

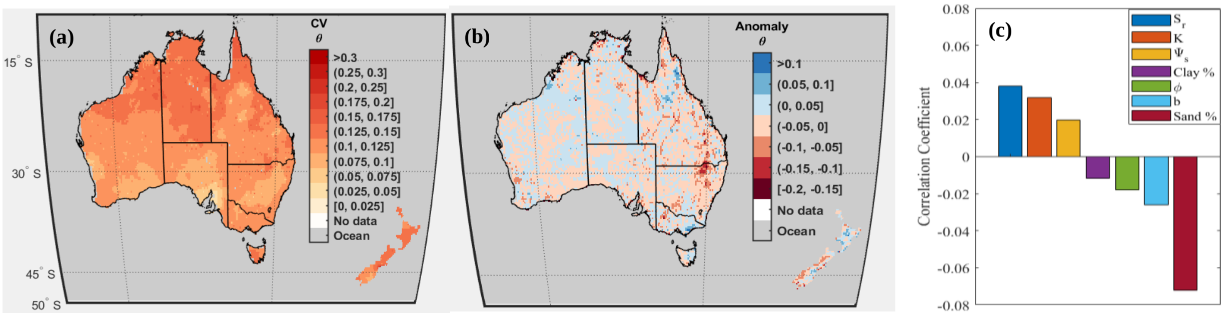

Figure 1. (a) Coefficient of Variation of moisture content. (b) Anomaly in moisture content. (c) Correlation coefficient between CV and water residual saturation (S_r), hydraulic conductivity (K), air entry suction (ψ_s), porosity (ϕ), pore volume distribution index (b), and clay and sand mass fraction.

The standard deviation of the stochastic θ in each grid cell from 2005 to 2014 was divided by the average over the same time period to find the coefficient of variation (CV). Here, we found that CV was higher in the northern regions of Australia and New Zealand as compared to the southern regions (Figure 1b). New Zealand consistently exhibits higher modelling variability as indicated by a generally higher CV and higher anomaly than seen in Australia.

We conclude that the variability in soil moisture content θ in the topsoil does not generally show a pattern correlated with the geography and soil properties of the region. As seen in figure 1(c), soil compositional, hydraulic, and physical properties have a weak correlation with the measured variability.

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Keywords: *Groundwater, soil, uncertainty, moisture content, Monte Carlo*

EXTENDED ABSTRACT ONLY

Parametric uncertainty in the continental scale landscape modelling

Ali Azarnivand [a], Wendy Sharples, Ulrike Bende-Michl, Ashkan Shokri, Andrew Frost and Stuart Baron-Hay

[a] *Bureau of Meteorology, Australia*
Email: Ali.azarnivand@bom.gov.au

Abstract: The soon to be released Bureau of Meteorology's Hydrological Projections provide national consistent data and information to assess impacts of climate change on Australia's water resources. The Hydrological Projections are generated via a modelling chain. This includes the use of climate inputs from general climate models (GCMs), a regional climate model (RCM), three bias-correction methods to produce climate forcing data used to run the Bureau's operational hydrological model, the Australian Water Resources Assessment Landscape model, AWRA-L v6.1 (Frost and Wright 2018). As part of the Hydrological Projection evaluation process, uncertainties associated with every part of the modelling chain are undertaken. In this study we evaluate the uncertainties associated with the hydrological modelling part of the modelling chain. We examined the overall model uncertainty as well as the parametric uncertainty. To ascertain the overall model uncertainty, a set of metrics capturing precision and reliability were chosen to apply to AWRA-L simulation outputs matching an observational period. Addressing the parametric uncertainty, a set of metrics were applied to outputs derived from a set of optimum Pareto solutions, which were extracted using an evolutionary multi-objective algorithm to optimize three objective functions across water balance components: runoff, actual evapotranspiration (ET) and top-layer soil moisture.

Owing to the complex nature of Australia's landscapes and climate regions, we present our uncertainty results across eight clusters of the aggregated Natural Resource Management (NRM) Regions (Figure 1). These regions represent similar physio geographic characteristics. This provides the opportunity to quantify the uncertainties of the simulated hydrologic responses by considering diversity in climate, land cover and topography across Australia using the reliability and precision metrics chosen.

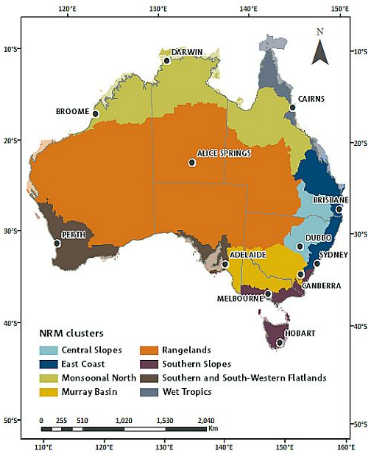

Figure 1. Map of the NRM cluster regions

To summarise the results of this study, parametric uncertainty analysis revealed that model parameters related to modelling baseflow and top-soil layer drainage are among the most uncertain. Model uncertainty analysis with respect to accuracy and reliability revealed that the Southern Slopes, Wet Tropics and East Coast regions are the most accurate and reliable simulated runoff, along with the lowest uncertainties in modelled ET, soil moisture and terrestrial water storage. The Monsoonal North also shows moderate levels of uncertainty. Conversely, arid and semi-arid regions such as Rangelands, Central Slopes and parts of Murry Basin, which are dominated by non-perennial streams and a high degree of dependency of baseflow to sustain runoff, generated larger levels of uncertainty, indicating that the subsurface baseflow contribution to the total streamflow runoff is another crucial factor affecting the reliability and precision of the results. Southern and South-Western Flatlands is another region with large levels of uncertainty, possibly due to ephemeral flows in that region. However, the number of un-impaired evaluation catchments plays a critical factor for this assessment. Regions with a higher number of evaluation catchments produce more stable results. Future work could include a gridded evaluation (e.g., GRACE, CCI) across the entire region to overcome this limitation for the water balance components. Overall, an acceptable level of uncertainty for simulated hydrology is shown, using AWRA-L v6.1. This study suggested future improvements with respect to simulating groundwater surface water interactions given that simulations for dry regions with non-perennial flows have highest uncertainties.

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Keywords: *Uncertainty analysis, Australian Water Resources Assessment Landscape model, Natural Resources Management (NRM) regions, groundwater-surface water interactions*

A novel dynamic connectivity metric for complex floodplain wetlands

Chi Nguyen, Edoardo Daly, and Valentijn R.N. Pauwels

Department of Civil Engineering, Monash University, Clayton, Victoria, Australia
Email: thi.nguyen3@monash.edu

Abstract: Hydrological connectivity is a crucial factor influencing the biodiversity and ecological integrity of many floodplain wetlands. Because of the shortage of high-resolution spatial and temporal data in many catchments, the mechanisms driving the changes in the connectivity of wetlands are not straightforward to investigate. Different connectivity metrics and indicators have been established using field measurements, remote sensing data, and hydraulic/hydrodynamic model results. However, current statistical connectivity metrics only consider the connectivity in a specific direction at a time, thus not being able to fully capture the connectivity in floodplain wetlands where water flows in different directions.

We propose a dynamic connectivity metric to analyze the spatial and temporal connectivity in floodplain wetlands, using the results from the two-dimensional hydraulic flood model LISFLOOD-FP. The dynamic connectivity metric includes the calculation of two lengths, referred to as the Total (TCL) and Dominant (DCL) Connection Lengths. The TCL calculates all possible travel distances from an input source to an inundated cell in the floodplain. The DCL considers the travel distance of the largest flow into each inundated cell. The dynamic changes in surface water connectivity are reflected in the relative frequency distribution of the DCL and the TCL, and the spatial patterns of the DCL. The method was applied to Back Lake and Clear Lake in the Narran River floodplain, in New South Wales, Australia.

Differently from existing connectivity metrics, the dynamic connectivity metric allows for the comparison of the hydrological connectivity in different phases of a flood event, between different flood events, and potentially across different catchments. Moreover, the new metric considers the connection following actual flow paths instead of along a particular direction. More information about hydrological connectivity can be obtained from the TCL and DCL analysis than from the modeled flood extents or remote sensing data. The backflow effect or the flood pulse from the lakes to the river during the recession can also be identified without additional complications to the method.

The application of the metric to our case study indicates that the hydrological connectivity mechanism depends on many factors, including the topography of the catchments. Consequently, the connectivity behavior in the flat Narran wetland can be expected to be distinctive from other wetlands with different topography features. There is no clear transition in the connectivity between different stages of a flood event in the flat Narran River wetland compared with other wetlands connecting to deeper river channels. The proposed metric brings a more comprehensive observation on hydrological connectivity in floodplain wetlands than previously developed metrics. The applications of the new metric are expected to support ecological research, flood management and forecasting, and the management of floodplain wetlands.

Keywords: *Surface water connectivity, hydrological connectivity, hydraulic modelling, floodplain wetland*

Modelling hydrological change due to wildfires

D. Partington [a], **M. Thyer** [b], **M. Shanafield** [a], **D. McInerney** [b], **S. Westra** [b], **H.R. Maier** [b], **C.T. Simmons** [a], **B.F.W. Croke** [c], **A.J. Jakeman** [c], **H.V. Gupta** [d] **and D. Kavetski** [b]

[a] *College of Science and Engineering, Flinders University, South Australia,* [b] *School of Civil, Environmental and Mining Engineering, University of Adelaide, South Australia,* [c] *Fenner School of Environment and Society, The Australian National University, Australian Capital Territory,* [d] *Hydrology and Atmospheric Sciences, University of Arizona, Arizona*
Email: daniel.partington@flinders.edu.au

Abstract: Wildfires are an important hydrological disturbance altering runoff by the fire induced changes (from heat and smoke) to vegetation and soils. The damage to both vegetation and soils creates immediate local changes to water portioning and associated runoff which can accumulate to catchment scale changes. Such changes are dynamic depend on the subsequent recovery of soils and regrowth/recovery of vegetation. As the prevalence of wildfires increases due to a warming and drying climate, such disturbances are a necessary consideration in the management and associated modelling of water resources. The impact of wildfires on water resources decisions comes not only in the immediate aftermath of the fires, but throughout the recovery phase and over extended periods with multiple cycles of wildfire and growth. Associated with these three timescales are pertinent hydrological issues, i.e. flood risk, water quality, water allocations and planning of reservoir operations. Modelling the wildfire induced hydrological impacts at each of these time-scales requires a focus on the dominant processes; hydroclimate/meteorological, vegetation, hydrological, fire spread and effects; the latter here is only of significance in consideration of future fires. Focusing on different levels of abstractions of the dominant processes has resulted in a diverse set of approaches across existing models. Here, we explore some of the existing models in the literature that have been applied in assessing wildfire induced changes to runoff. For the purposes of comparison we broadly categorise these models into one of three categories: data-driven, conceptual and physically-based (eco-)hydrological models. We consider their demonstrated applications (assessing changes to streamflow and baseflow, historical analysis of pre- and post-fire periods of streamflow, predicting long term changes to yield), process representations (implicit vs explicit, lumped vs distributed) and spatiotemporal scales (from plot scales over days to watersheds over decades). Based on these characteristics and considering the computational requirements, data type breadth needed and the ability to predict wildfire impacts on runoff for different fires in the future, we describe the key limitations of each model category. With the significant changes to hydrological functioning that are possible after wildfire, physically-based models that utilize physical and biological principals are likely to receive increased attention with their perceived ability to extrapolate outside of the historical record. However, the computational and data costs of physically-based models are limiting the ability to completely support water resources planning. We argue that overcoming such limitations, while leveraging strengths, is possible through adoption of a hybrid modelling approach which combines computationally efficient conceptual models with reduced-order models. Such a hybrid approach would enable the requisite simulations of wildfire-induced changes to runoff for critical water resources planning scenarios.

Keywords: *Disturbance hydrology, wildfire, hydrological change, hydrological modelling*

Calibrating continental-scale hydrological models to future climate conditions

W. Sharples [a], A. Shokri [a], A. Frost [a], U. Bende-Michl [a], L. Wilson [b] and S. Baron-Hay[a]

[a] *Bureau of Meteorology, Australia*
[b] *Meteorological Office, UK*
Email: wendy.sharples@bom.gov.au

Abstract: Australian hydrological characteristics are varied with many river systems exhibiting ephemeral flow, large areas with flat topography, frequent occurrence of hydrological extremes such as droughts and floods, complex surface-groundwater interactions and high-levels of water management and interception, culminating in significantly different hydroclimatic regions. Consequently, calibrating a large-scale hydrological model to Australian hydroclimate conditions is not trivial. To further compound this issue, hydroclimatic observations are sparse in many areas across Australia.

Australia's hydroclimate is predicted to and has already been observed to change, noting that Australia has warmed by 1.4ºC since 1910. Thus, providing nationally consistent hydroclimate forecasts and projections along with a historical context, is essential for Australia's population to mitigate the negative socio-economic impacts of a changing hydroclimate. Therefore, to improve the skill of forecasts and confidence in projections of the future state of Australia's hydroclimate, calibrating a large-scale model to future changes would be advantageous.

We propose a two-step method to tune a continental model to present climate and possible future climate changes, using the Bureau of Meteorology's landscape water balance model, AWRA-L (Frost and Wright 2018). For the optimisation process we have used a multi-objective evolutionary algorithm, BorgMOEA (Hadka and Reed 2013 - See Figure 1), to examine trade-offs between water balance components, wet and dry climate scenarios and different hydroclimatic regions. To improve the stability and reliability of the calibration process, we have employed Variance-Based Sensitivity analysis (VBS; Saltelli et al. 2009) to reduce parametric dimensionality. By employing firstly, VBS and then BorgMOEA, an optimal set of model parameters or suite of parameter sets can be found which satisfy both current and future climate conditions according to user requirements. In this study we detail this method using AWRA-L and provide an evaluation of the resulting optimal parameter sets. We show that whilst no one parameter set "fits all" scenarios, this approach can provide a model configuration which "fits most".

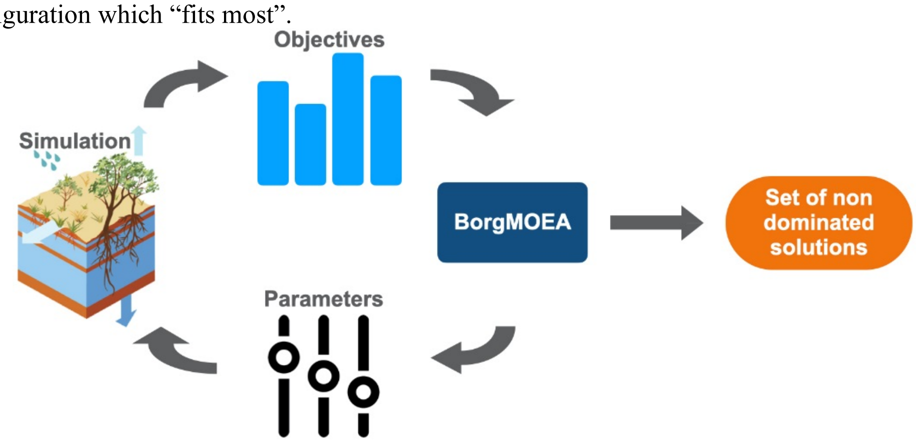

Figure 1. Schematic of the multi-objective optimisation process

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Keywords: *Model calibration, continental scale hydrology, trade-off analysis, climate change, AWRA-L*

Accelerating development of the next generation of conceptual hydrological models to support decision-making under change

Mark Thyer [a], Hoshin Gupta [b], Seth Westra [a], David McInerney [a], Holger Maier [a], Dmitri Kavetski [a], Tony Jakeman [c], Barry Croke [c], Craig Simmons [d], Margaret Shanafield [d] and Daniel Partington [d]

[a] *School of Civil, Environmental and Mining Engineering, University of Adelaide, SA, Australia*
[b] *Hydrology and Atmospheric Sciences, University of Arizona, Arizona, USA*
[c]*Fenner School of Environment, Australian National University, Canberra, SA, Australia*
[d] *College of Science and Engineering, Flinders University, SA, Australia*

Email: mark.thyer@adelaide.edu.au

Abstract: Predictive skill in hydrology has been forged on the application of sophisticated calibration algorithms informed by ever-more-abundant historical data records. As this skill is confronted by rapid and multi-faceted change, and hydrological systems are pushed outside of their envelopes of historical experience, new thinking will be needed. Our current suite of conceptual models have limited ability to deal with hydrological change. The key challenge is that principal hydrological lines of evidence (HLE's), such as experimental/paired catchments, large sample hydrology etc, that in the past have been used to inform process understanding and its incorporation into hydrological models are largely limited to taking *'observational'* approach. This is where the researcher simply observes the systems response to changes (e.g., climatic phenomena). Two key drawbacks of this 'observational' approach are that uncontrolled confounding factors (e.g changes in vegetation/land-use/water management etc) make it difficult to determine causation and one may have to wait a long time to obtain observations of rare climatic phenomena (e.g. extreme droughts or large floods). We argue that "virtual hydrological laboratory" is a new HLE that provides a unique opportunity to undertake "controlled experiments" of the robustness our hydrological models to hydrological changes, overcome the drawbacks of the observational approach. This will complement existing HLE's and lead to new generation of conceptual models (change-informed reduced-order models or CIROM's) that could become our most important workhorse for prediction and practical decision making. Specifically, we propose a way to ensure that they serve as agents that represent our best available scientific understanding, firmly founded upon the multiple available lines of hydrological evidence (see Figure 1) and integrated through the use of virtual hydrological laboratories to evaluate robustness to hydrological change via virtual experiments. Such models will enable us to move beyond 'predictive skill', measured using simple metrics of historical model performance, and facilitate 'getting the right answers for the right reasons'. This is more than a scientific curiosity; it is expected by policy makers who want to know what they need to plan for.

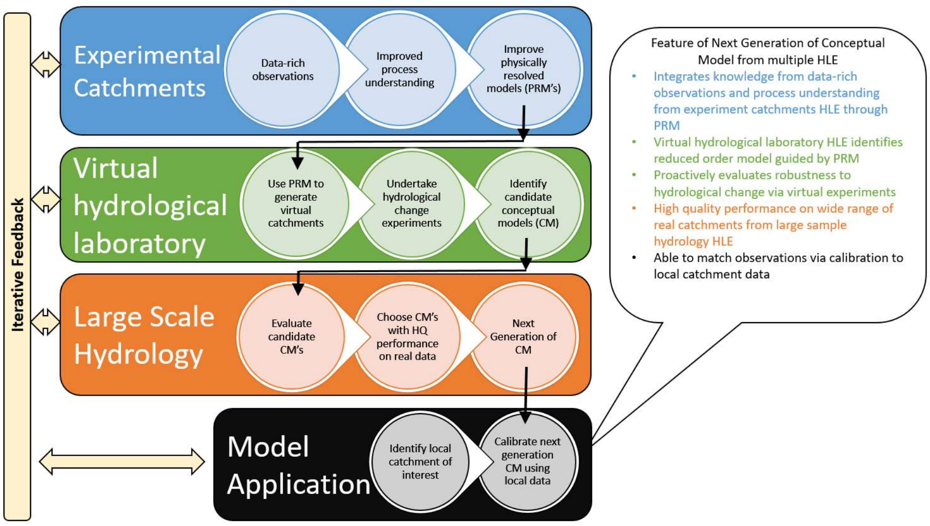

Figure 1. Integration of multiple hydrological lines of evidence using a VHL to provide the best available scientific understanding and develop the next generation of conceptual models

Keywords:

“Naïve” inclusion of diverse climates in calibration is not sufficient to improve model reliability under future climate uncertainty

L. Trotter [a], **M. Saft** [a], **M.C. Peel** [a] **and K.J.A. Fowler** [a]

[a] *Department of Infrastructure Engineering, University of Melbourne, Melbourne, Australia*
Email: l.trotter@unimelb.edu.au

Abstract: Parameter sets of hydrologic models do not transfer well between periods with different climatic conditions. Existing literature shows that model performance is particularly affected when parameters calibrated on wetter conditions are used to project streamflow during drier conditions. In the Australian context, where future projections indicate the climate is likely to become warmer and drier as a result of global climate changes, these limitations of hydrologic models become particularly disquieting, especially with regards to their implications for estimating water availability during dry periods. The Millennium drought, which impacted large parts of south-eastern Australia ca. 1997-2009, exposed these limitations of hydrologic models and their most common calibration methods. During the drought, many catchments in south-eastern Australia underwent changes in their hydrologic behaviour. Extensive research since the end of the drought shows that models calibrated on pre-drought conditions routinely overestimate streamflow when forced with climate data from the years of the drought.

In operational simulation, it is often assumed that once a model is shown a variety of climate conditions in the calibration sequence, it will perform better under future climate variability. In the context of the Millennium drought, it has been theorised that now that we have experienced these conditions, models calibrated on long timeseries that include the Millennium drought will be able to perform well under a future drier climate. In this study, we put this idea to the test. Specifically, we use five commonly used conceptual hydrologic models and evaluate their performance during and after the Millennium drought in 155 Victorian catchments. We test whether their performance (in terms of KGE and bias) improves significantly after inclusion in the calibration period of the drought and the post-drought periods themselves. For calibration we use an objective function specifically designed to optimise models’ ability to reproduce both high and low flow conditions while minimising volumetric bias.

Our results show that the “naïve” approach of extending calibration sequences to include as much climate diversity as possible is not sufficient to significantly improve model reliability in the face of future climate uncertainty. We demonstrate that showing models data from the Millennium drought in calibration did not significantly improve their performance across this set of catchments, neither during the drought itself nor, in most cases, in the period after the drought. Further including the post-drought sequence in calibration does significantly improve post-MD KGE in three out of five models, but even in these models, performance is still significantly lower than it is when calibrating on post-drought only and the improvement, albeit statistically significant, is unlikely to make operational difference in most cases. Additionally, bias doesn’t significantly change. This is despite drought and post-drought making up a significant proportion of the calibration sequence (at least 30%). Mann-Whitney tests were used to assess whether model performance was significantly different across the set of catchments. Our results also show that, while rarely significant, the extension of the calibration period does provide a marginal improvement in performance for almost all models and both periods tested. This is encouraging and supports the practice to expose models to a variety of climate conditions, however it indicates that additional provisions are needed when training models for use in ungauged climates.

Evidence from literature suggests that more sophisticated calibration methods with explicit and distinct treatment of different climate regimes improve model performance under a transient climate. However, especially in the catchments where drastic shifts were observed, new model structures that are more flexible to such climate-induced changes in hydrologic regime are likely necessary to confidently project streamflow under future climate scenarios. By exposing these limitations, we encourage members of the hydrologic community to exercise caution when applying our existing models and calibration frameworks to project streamflow into unknown and uncertain climate conditions. We also join the numerous community calls for new and more robust approaches for hydrologic modelling and simulation in the face of a changing climate.

Keywords: *Hydrologic models, calibration, climate variability, Millennium drought*

Do larger catchments respond different to forest cover change? Re-analysing global data sets

R. Willem Vervoort[a,b], **Eliana Nervi**[c] **and Jimena Alonso**[d]

[a]ARC IITC DARE, [b]The University of Sydney, Australia, [c]Project manager FPTA 358, [d]IMFIA, School of Engineering, Universidad de la República, Uruguay
Email: willem.vervoort@sydney.edu.au

Abstract: Recently, three summary papers (Filoso et al., 2017; Zhang et al., 2017; Zhou et al., 2015) review and analyse large global datasets related to impacts of forest cover on streamflow. Using three different approaches, they all find a strong relationship between forestation/de-forestation and streamflow. However, all studies indicate different confounding factors on the impact of forestation. Particularly, two of the studies point to a relationship between catchment area and magnitude of the impact, while the third highlights the relationship between aridity and impact. The past approaches in the literature are variable and can be substantially improved in statistical rigour. Therefore, the data these three papers were reviewed, combined and re-analysed to answer the following new and older questions: 1) How is streamflow impacted by the change in forest cover as a function of catchment area; 2) how is this relationship conditioned by the length of the study, and climate; and 3) do the reported method, the age of the study and other possible variables impact the observed change in streamflow? Generalised additive models were used to run flexible regressions including multiple variables. The results indicate that, changes in forest cover still cause changes in streamflow, however this change is different between deforestation and reforestation, and also affected by climate, with warmer climates (closer to the equator) indicating larger changes in streamflow. Deforestation causes a 32% greater change in flow compared to reforestation. In contrast to the older work, there is no indication that the area of the catchment affected the results, but this is potentially caused by the wide variety in reported results from small scale paired catchment studies (Figure 1). These smaller studies also dominate the database with 42% of the data < 1 km^2 and 65% of the data < 10 km^2. As a result, the paired catchment study assessment technique increased the change in flow by 135% in the model. Length of the study and initial year of the study did not affect the change in flow, in contrast to other reported studies. These results provide new insights in the impacts of forest cover change on hydrology but also indicate many unanswered questions in the relationship.

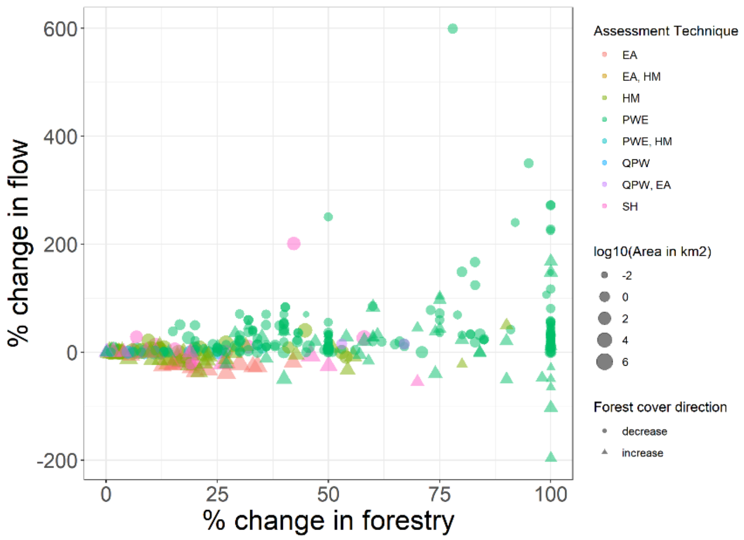

Figure 1. Relationship between change in forest cover and change in streamflow. EA is elasticity analysis, HM is hydrological modelling, PWE is paired watershed experiment, QPW is quasi-paired watershed experiment and SH is combined statistical and hydrograph analysis (after Zhang et al. 2017)

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Keywords: *Statistical analysis, forestry streamflow connection, quantitative literature review*

Modelling hydrologic non-stationarity for robust projections of water futures

Francis HS Chiew[a], Hongxing Zheng[a], David E Robertson[b] and Julien Lerat[a]

[a]CSIRO Land and Water, Black Mountain, Canberra
[b]CSIRO Land and Water, Clayton, Melbourne
Email: francis.chiew@csiro.au

Abstract: The calibration of hydrological models tends to lead to runoff underestimation in wet periods and runoff overestimation in dry periods. This is particularly evident in catchments with significantly contrasting dry and wet periods, like the very different rainfall-runoff response in catchments in Victoria in south-east Australia during the long and severe 1997–2009 Millennium drought (and post drought) compared to the response before the drought. When used in climate change impact studies, hydrological models will therefore tend to underestimate the range in the projected future hydrological impact. That is, the models will likely underestimate the decline in future runoff where a runoff decrease is projected and overestimate the increase in runoff where a future runoff increase in projected.

Various approaches have been proposed and explored to more robustly model hydrologic non-stationarity, that is, the changing rainfall-runoff relationship. The most satisfying approach is probably to improve the conceptualisation of the dominant hydrological processes under all hydroclimate conditions, that is, to develop the "perfect" hydrological model. Some studies explore changing parameter values dependent on the climate inputs or storage states. Other studies have explored smarter calibration strategies, like robust calibration against multiple objectives to produce good simulations of dry periods as well as wet periods at the expense of the traditional 'best' simulation over the entire period of record.

This paper presents results from some of these approaches and proposes a method to diagnose the improvement in the robust modelling. The method is largely based on the modelling ability to reproduce the time series of annual runoff (or any runoff characteristic), measured by (i) aggregated absolute errors over the simulation period, (ii) relative error (systematic bias) in the driest years (overestimation) and wettest years (underestimation), and (iii) overall bias over the full period (this is important because the intrinsic systematic bias of any calibration method would propagate from the baseline calibration period, and the systematic bias would largely be cancelled out when estimating the relative runoff change when comparing the modelled future runoff against different modelled baseline runoff).

Acknowledgements: This research is supported by CSIRO, Victorian Water and Climate Initiative (VicWaCI) and Murray Darling Water and Environmental Research Program (MD-WERP).

Keywords: *Hydrologic non-stationarity, hydrological modelling, robust calibration, hydrological projections*

How sensitive are streamflow projections to shifts in rainfall runoff relationships?

Keirnan Fowler[a], **Avril Horne**[a], **Connor McCutcheon**[b], **Rory Nathan**[a], **Murray Peel**[a], **Tim Peterson**[c], **Margarita Saft**[a] **and Robert Wilby**[d]

[a] Department of Infrastructure Engineering, University of Melbourne, Parkville, 3010, Australia
[b] Victorian Department of Environment, Land, Water and Planning, East Melbourne, 3002, Australia
[c] Department of Civil Engineering, Monash University, Clayton, 3800, Australia
[d] Department of Geography, Loughborough University, Loughborough, United Kingdom
Email: fowler.k@unimelb.edu.au

Abstract: We have known for some time that the relationship between annual rainfall and annual runoff may shift during multi-year drought, and that these shifts are typically associated with poor performance of commonly used hydrological models. However, few articles examine the implications for water planning under climate change. If multi-year drought is the best analogue we have for a permanently drier future, then the model bias and performance problems observed for historic drought will also affect the quality of hydrological projections (in cases of future drying). Commonly-used hydrological models poorly represent historic shifting behaviour and cannot be relied upon to anticipate future shifts. Thus, their use may result in underestimation of hydroclimatic risk and exposure to "surprise" reductions in water supply, relative to projections.

Here, we seek to advance dialogue on these issues by presenting numerical experiments that explore the scale of the challenge in the context of both historic events (the Millennium Drought) and climate change. Due to the shifting behaviour, hydrological models calibrated to the pre-Millennium Drought period often significantly overestimate streamflow during the drought (see figure), even though they take the drought's lower rainfall into account in producing the simulation. Further, the observed shift in behaviour creates challenges for future projection because the projected water availability diverges significantly depending on the historic period used for calibration. Here, to quantify this divergence, separate projections are undertaken using periods before and after the hydrological shift, respectively. The alternative projections reflect different assumptions regarding drought recovery: projections based on the post-shift calibration period provide a non-recovery scenario ("new normal" in the figure) whereas pre-shift projections assume recovery ("old normal" in the figure). The divergence in outcome is large – even in the context of future drier climate – and thus significant uncertainty arises from the possibility of future shifting behaviour. Such behaviour could include a historically shifted catchment shifting further in future ("unseen future normal" in figure), or a historically stable catchment shifting for the first time in future.

Overall, the results underscore the need to invest in hydrological process understanding, especially around drought recovery, and their representation in modelling tools. The onus is now on hydrologists to determine the underlying causes of shifting behaviour and incorporate more dynamic realism into operational models.

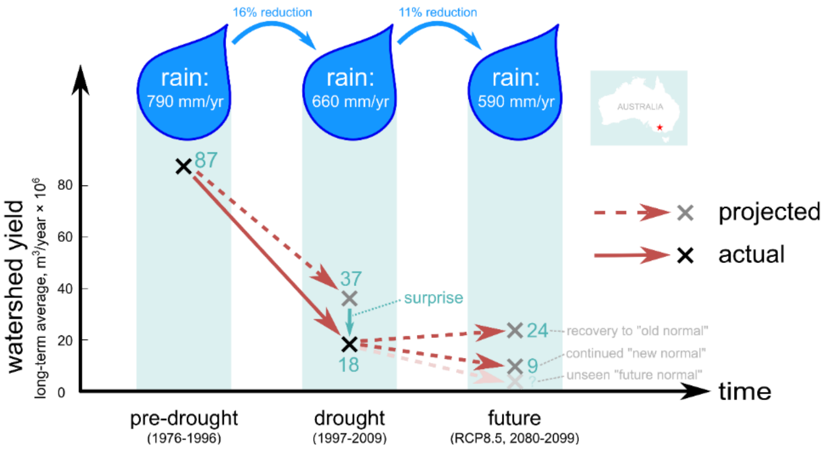

Figure 1. Watershed yield history and projections for Victoria's Campaspe River (406213). Projections based on hydrological model GR4J and (for 'future') forced using dynamically downscaled MIROC5 GCM projections.

Keywords: *Rainfall-runoff relationship, climate change, streamflow projections, drought*

Non-stationary influences of climate drivers on low streamflow extremes

Pallavi Goswami [a], Tim J. Peterson [b], Arpita Mondal [c,d] and Christoph Rüdiger [b,e]

[a] IITB Monash Research Academy, IIT Bombay, Mumbai, India
[b] Department of Civil Engineering, Monash University, Clayton, Victoria, Australia
[c] Department of Civil Engineering, Indian Institute of Technology Bombay, Mumbai, India
[d] Interdisciplinary Program in Climate Studies, Indian Institute of Technology Bombay, Mumbai, India
[e] Bureau of Meteorology, Melbourne, Victoria, Australia
Email: Pallavi.Goswami@monash.edu

Abstract: The dry phase of the El Niño-Southern Oscillation, the Indian Ocean Dipole, and the Southern Annular Mode have been known to influence drought periods in southeast Australia (SEA). These can modulate the processes generating runoff, thereby leading to lower streamflow. There is emerging evidence that the activity of large-scale climate modes might undergo amplification in a warming scenario (Cai et al., 2014; Cai et al., 2015). Given their likely future changes, and the demonstrated impact of such changes on precipitation events (Lim et al., 2016), low flow characteristics may be non-stationary in time due to the influences from such climate drivers. To this end, we investigated the low flow intensity, duration, and frequency (IDF) non-stationarity. Low flow events, defined as spells when the deseasonalised flow depth is below a suitably chosen threshold, were identified for 161 unregulated catchments in SEA (data from Peterson et al., 2021). The influences of the climate modes on the low flow intensities were modelled using extreme value distributions, while the influence on duration and annual frequency of the low flow events were modelled using generalized linear models.

We found that the low flow IDFs for several of the study catchments exhibit strong non-stationary influences from these climate modes. These catchments have a higher probability of experiencing more prolonged and frequent low flow spells during the dry phase of these climate drivers (as seen in Fig. 1a and 1b where the orange curve is seen to be associated with higher values of duration and frequency than the blue curve). The effect on intensity is, however, not appreciably large. Further, using CMIP5 RCP8.5 projections, the projected series of the climate indices were derived. These series indicate an intensification in the dry phase of the climate drivers. Using these in the IDF models, we found that future dry phases of the climate drivers are likely to make low flow periods, or hydrological droughts in turn, more frequent and of longer duration (as seen in Fig. 1c and 1d in the form of shift of the red curve from the orange curve towards higher values of duration and frequency) but possibly not more extreme in their magnitude. In addition, low flow events were generally found to occur during winter and spring. Since low flows studied here were obtained using deseasonalised anomalies, the results suggest that winter and spring will likely be experiencing longer and more frequent low flow spells during future dry phases of these climate modes.

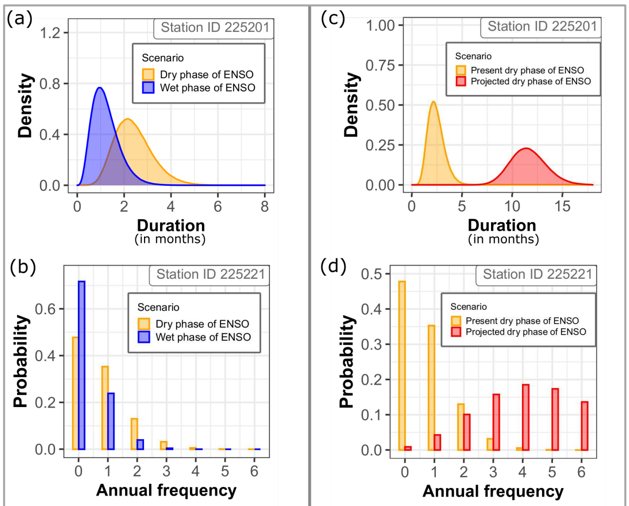

Figure 1: Probability density of (a, c) duration and (b, d) frequency of low flows corresponding to the dry phase of ENSO in constrast to a wet phase (left column), and the projected future dry phase of ENSO in contrast to the present dry phase (right column).

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Keywords: *Low flows, non-stationarity, droughts, climate teleconnections, Extreme Value Theory*

Recent increase in Northern Australian streamflow unmatched over the past 600 years

P. A. Higgins[1,2], **J. G. Palmer**[2,3,4], **M. P. Rao**[5,6,7], **M. S. Andersen**[8], **C. S. M. Turney**[2,3,4], **and F. Johnson**[1]

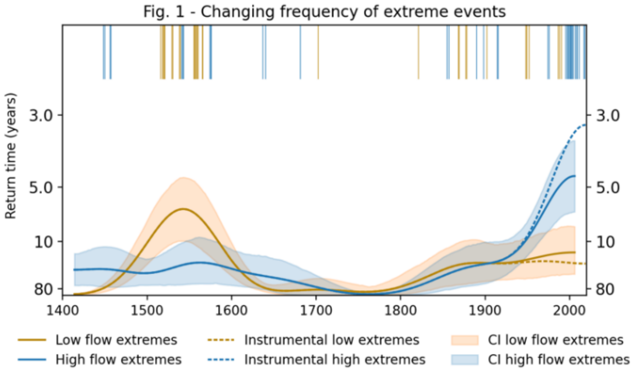
[1] Water Research Centre, School of Civil and Environmental Engineering, University of New South Wales, Australia. [2] ARC Centre of Excellence in Australian Biodiversity and Heritage, University of New South Wales, Australia. [3] Chronos [14]Carbon-Cycle Facility, Mark Wainwright Analytical Centre, University of New South Wales, Australia. [4] Earth and Sustainability Science Research Centre, School of Biological, Earth and Environmental Sciences, University of New South Wales, NSW 2515, Australia [5] Cooperative Programs for the Advancement of Earth System Science, University Corporation for Atmospheric Research, USA [6] Department of Plant Science, University of California, USA [7] Tree-ring Laboratory, Lamont-Doherty Earth Observatory of Columbia University, USA. [8] Water Research Laboratory, School of Civil and Environmental Engineering, University of New South Wales, Australia.
Email: philippa.higgins@unsw.edu.au

Abstract: Large-scale agricultural development has been proposed for the Daly catchment in the Northern Territory of Australia. Since the start of record keeping in the Daly catchment in the 1970s, streamflow has been steadily increasing, most likely due to increases in Australian monsoon rainfall. Despite this increasing trend, rainfall variability remains high; consecutive years of monsoon failure occurred during the 2018–19 and 2019–20 wet seasons, resulting in very low river levels and water restrictions over much of Australia's north. Climate models predict a future increase in monsoon rainfall variability, which has important implications for the management of water resources in catchments like the Daly where water storage potential is limited. As streamflow gauge records from the Daly catchment are short, it is hard to assess this recent trend and therefore understand the potential impacts of increased development and water use.

In this study, we produced a paleo-streamflow reconstruction of the Daly catchment from 1413 to 2005 CE using a network of 63 precipitation-sensitive tree-ring chronologies from the Indo-Australian and Asian monsoon regions. Building on the work of Jiang et al. (2020) and Jiang et al. (2021), we used a novel wavelet-based method to transform the variance structure of the tree-ring chronologies to better match the hydroclimate. A nested hierarchical Bayesian regression model with partial pooling, which is suitable for our short streamflow gauge records with missing years, was then used to produce the reconstruction from the transformed chronologies. The wavelet transform was shown to substantially strengthen the correlation between the tree-ring predictors and Daly catchment streamflow and improved the calibration and validation statistics over the reconstruction interval. Our final streamflow reconstruction accounts for 70-76% of the variance in the instrumental period and closely matches both historical flood events and independent proxy records, increasing confidence in its validity.

We find that while streamflow has been increasing since the 1800s, the most recent 40-year period of high streamflow is unprecedented in the last ~600 years (Fig. 1). Extreme high flows were found to be linked to La Niña events, but we found no significant relationship between streamflow and El Niño events, confirming that Australian monsoon rainfall responds asymmetrically to the El Niño-Southern Oscillation. The mechanisms behind the increasing trend in monsoon rainfall, and thus streamflow, are currently unknown. More work is therefore needed to understand the drivers of the recent streamflow increase, but, regardless of the cause, water managers should be aware of the paleoclimatic context before making decisions on water allocations.

Fig. 1 - Changing frequency of extreme events



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Keywords: *Paleo-streamflow, dendrochronology, flood frequency, recurrence interval*

Predicting runoff in a drier future with limited data: A case study

J.D. Hughes [a], B. Wang [a] and R.J. George [b]

[a] CSIRO, Land and Water [b] Western Australian Department of Primary Industries and Regional Development
Email: justin.hughes@csiro.au

Abstract: Hydrological prediction is still largely reliant on conceptual models. However, climate change, both observed and expected, mean that hydrologists are increasingly required to estimate runoff or other hydrological variables outside of the conditions of available calibration data. Furthermore, conceptual models have been shown to be unreliable where simulation conditions are substantially different from calibration, particularly where simulation conditions are drier than calibration conditions (e.g. Vaze et al., 2010).

A drying climate has revealed that rainfall-runoff relationships across southern Australia may change (e.g. Petrone et al., 2010, Saft et al., 2015) further exacerbating the hydrologists conundrum. This in turn has exposed some weaknesses in conceptual models leading to testing of alternative conceptual model formulations that incorporate catchment responses to long-term drying (e.g. Hughes et al., 2013; Fowler et al., 2021). However, while the tools available for prediction are improving, how are they best applied in a drying climate?

This study demonstrates how one may use the newer model formulations in a drying climate, with limited available data. A specific example is used to demonstrate potential solutions where predictions are required despite the difficulties. This case study demonstrates that a range of novel constraints are necessary for better prediction even with, or perhaps especially with, newer conceptual models. Additionally, the value of a rainfall – runoff data library for guiding the calibration end evaluation process is discussed.

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Keywords: *Non-stationarity, rainfall – runoff, conceptual models, data library, calibration*

A simple state-based approach to improve streamflow predictions under changing catchment conditions: An example application with IHACRES

Takuya Iwanaga[a], **Barry F.W. Croke**[a,b], **Qian Wang**[c] **and Anthony J. Jakeman**[a]

[a] *Institute for Water Futures and Fenner School of Environment and Society, The Australian National University, Canberra, Australia*
[b] *Mathematical Science Institute, the Australian National University, Australia*
[c] *State Key Laboratory of Hydrology – Water Resources and Hydraulic Engineering, Center for Global Change and Water Cycle, Hohai University, Nanjing 210098, China*
Email: iwanaga.takuya@anu.edu.au

Abstract: Applications of conceptual hydrological models often rely on a single parameter set calibrated to historical conditions under the assumption of temporal non-stationarity. At the same time, climatic and catchment conditions are expected to shift, inducing new catchment behaviours, likely leading to a deterioration in a model's predictive skill. Ensemble modelling approaches have been put forth as a potential avenue to meet this challenge.

A state-based ensemble modelling approach is described in this presentation. The approach adopts time-varying parameter sets to explicitly consider temporally changing catchment conditions inferred from the range and distribution of modelled catchment moisture deficit conditions. Predictions from individual model instances combined with a simple weighted average are shown to achieve improved "goodness-of-fit" under a variety of conditions relative to a conceptual model calibrated with a single parameter set.

The approach is showcased with the IHACRES conceptual rainfall-runoff model applied to a selection of five catchments around the Australian Capital Territory. The demonstrated approach is expected to be generic and applicable to any conceptual model, which includes indications of catchment state. Lesser computational requirements compared to other ensemble approaches is also expected. We additionally discuss current limitations and further possible improvements.

Keywords: *Hydrological modelling, conceptual modelling, ensemble modelling, state-based*

Modelling river transmission losses under changing hydrological regimes

S.S.H. Kim [a,b], **J.D. Hughes** [b], **L.A. Marshall** [a], **C. Petheram** [b], **A. Sharma** [a], **J. Vaze** [b] and **R.S. Crosbie** [b]

[a] *School of Civil and Environmental Engineering, University of New South Wales* [b] *CSIRO, Land and Water*
Email: shaun.kim@csiro.au

Abstract: Transmission losses often make up significant portions of the river water balance, particularly in arid environments. For the assessment of proposed water resource development plans, such as the Bradfield Scheme (Bradfield, 1941), accurate estimates of river transmission losses are required. With rising concerns for water security, accounting for transmission losses in water budgets is a central task but is challenging especially considering hydrologic and climatic non-stationarity. Direct field-based measurements of transmission losses are often impractical at basin scales. Transmission loss estimates are usually confounded with many different processes including floodplain storage, local runoff, evapotranspiration, river to groundwater exchanges and infiltration to deep aquifers. Furthermore, deterministic river loss estimates based on pre-developed environments are likely to be inappropriate for direct use in proposed scenarios since developments will significantly alter river behaviour and, thus, also change loss processes.

A common deficiency in existing river system loss models is the lack of a dynamic representation of river losses to groundwater, which is especially important in arid environments with low groundwater tables. To address this, a new simple conceptual model is under development that represents the relevant river processes including rainfall runoff, river loss/gain to/from groundwater, river rainfall/evaporation and routing on a reach-by-reach basis. A critical process of the new model is the loss of river water to a groundwater store, called the river bed/bank store, which occurs river volumes are relatively high. Conversely, the groundwater store can discharge water back when river volumes are relatively low. The model is designed to be transposable between different periods, such as pre- and post-developments, assuming sufficient data exist during calibration.

The new river loss model requires five calibrated parameters. An explicit Bayesian formulation and groundwater, remotely sensed evapotranspiration and streamflow data allowed investigation into the river loss model, using a test case in the Cooper Basin, Australia, which is a region associated with multiple proposed developments that would impact water resources. According to Knighton and Nanson (1994), without knowledge of the spatial and temporal variation of the losses, standard flow routing methods are difficult if not impossible to apply in the Cooper. The complex and dominant river loss processes, and its national relevance, make the Cooper Basin ideal for testing a new parsimonious river loss model. In the new model, the river to groundwater loss is calculated as a function of the river bed/bank store volume:

$$l_t = \left(s_t^{\text{cap}} - s_{t-1}\right)\left(1 - \exp(-k)\right) , \tag{1}$$

where l_t denotes the volume of water lost at time step, t, from the river to the river bed/bank store, s_t. s_t^{cap} is the river bed/bank store capacity at time step, t, and k is the parameter that controls the rate of infiltration. s_t^{cap} is dependent on the area of wetted surface, thus, s_t^{cap} is assumed to vary with river volume:

$$s_t^{\text{cap}} = \omega v_t , \tag{2}$$

where ω is the factor that sets the size of s_t^{cap} relative to v_t, which is the river volume at time step, t, determined from river routing equations. Note, when s_{t-1} is larger than s_t^{cap}, negative l_t values are produced, representing gains from groundwater to the river. The discharge using the new transmission loss model was compared to that of a benchmark (flow vs loss) model in a range of calibration and validation metrics. Future developments include coupling to the groundwater component of the rainfall runoff model.

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Keywords: *Transmission losses, river system model, calibration, uncertainty, Cooper Basin*

INVITED PAPER

EXTENDED ABSTRACT ONLY

Catchment may not recover from drought

Tim J. Peterson[a], **Margarita Saft**[b], **Murray C. Peel**[b] **and Andrew John**[b]

[a] *Department of Civil Engineering, Monash University, Clayton, Victoria, Australia.*
[b] *Department of Infrastructure Engineering, University of Melbourne, Victoria, Australia.*
Email: tim.peterson@monash.edu

Abstract: Almost all hydrological models behave so that after a disturbance of any magnitude, such as a drought, the catchment eventually recovers (Peterson et al. 2014). Hence, catchments have been assumed to be infinitely resilient. Here we present findings from our recent paper in *Science* (Peterson et al., 2021) that challenges this assumption. We statistically identified if and when runoff from unregulated catchments in Victoria (n=161) recovered from the Millennium Drought using annual and seasonal Hidden Markov Models.

We found three response and recovery dynamics: (i) no change during or after drought (Fig 1AB); (ii) reduced runoff per mm of rainfall during the drought and rapid recovery (Fig 1CD) and (iii) reduced runoff per mm of rainfall during and after the drought, and hence non-recovery (Fig 1EF). Across Victoria, ~30% of catchments had not recovered from the Millennium Drought by mid-2017; of which ~80% show no evidence of changing from this low runoff state. The non-recovered catchments are spread throughout much of the state, suggesting that both local scale catchment factors and regional climate factors are important. The causal mechanism for the non-recovery is likely to be increased post-drought transpiration (as a % of precipitation).

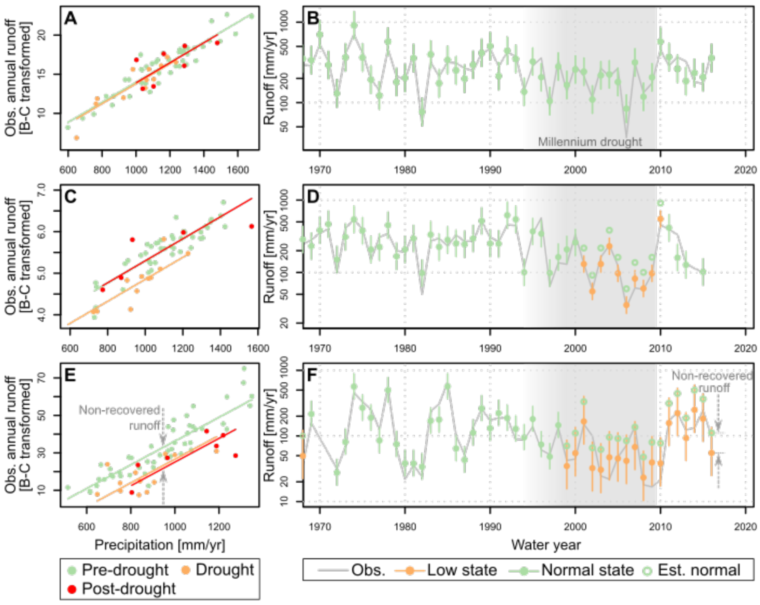

Figure 1. Three examples of how catchment rainfall-runoff may respond and recover (or otherwise) from a drought. (A-B) Wonnangatta River (224206) did not change during or after the Millennium Drought. (C-D) Yea River (405217) declined during the drought and appears to have recovered. (E-F) Cann River (221201) declined during and after the drought and appears not to have recovered. LHS shows regression results. RHS shows hidden Markov modelling results. Source: Peterson et al. (2021).

Our findings show that hydrological droughts can persist long after a meteorological drought, and the underlying theory suggests recovery is likely to occur only after very wet years. In an accompanying perspective piece within Science, Flavia Tauro says Peterson et al. (2021) "*challenges the comforting assumption that water systems naturally tend to absorb disturbances. This emphasizes the necessity to change the way global water processes are conceptualized.*" (Tauro, 2021). That is, our assumption of catchments having an infinite resilience appears wrong.

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Keywords: *Hydrology, ecosystem resilience, drought, hidden Markov modelling*

Spatial patterns in ecohydrologic response to climate change across a virtual catchment

Clare Stephens[1], Lucy Marshall[2], Fiona Johnson[2], Larry Band[3,4], Hoori Ajami[5] and Laurence Lin[3]

[1]*Hawkesbury Institute for the Environment, Western Sydney University, Richmond, NSW, Australia*
[2]*Water Research Centre, School of Civil and Environmental Engineering, UNSW Sydney, NSW, Australia*
[3]*Department of Environmental Science, University of Virginia, Charlottesville, VA, USA*
[4]*Department of Engineering Systems and Environment, University of Virginia, Charlottesville, VA, USA*
[5]*Department of Environmental Sciences, University of California, Riverside, CA, USA*
Email: c.stephens@westernsydney.edu.au

Abstract: Complex interactions between changing climate, vegetation dynamics and hydrologic processes will affect future catchment dynamics. These impacts are likely to vary across space due to heterogeneity in factors like terrain, soil type and nutrient availability. However, this spatial complexity is often ignored in catchment-scale assessments of future ecohydrologic shifts. We used RHESSys – a process-based ecohydrologic model that simulates dynamic vegetation growth, nutrient cycling, and explicit hydrologic routing – to investigate the drivers of altered catchment dynamics under future climate scenarios with a particular focus on spatial patterns of change across a 12.5 ha catchment. We simulated both wetter and drier scenarios, with temperature and CO_2 increases based on the IPCC RCP8.5 projections.

We found substantial heterogeneity in climate change impacts across the catchment, driven largely by water and nutrient transport that created subsidy effects. For example, decreased growth in water-limited upstream areas under drying conditions coincided with increased growth in the riparian areas. This response occurred because nutrients that would have been taken up by the upstream vegetation were instead transported downstream, where water availability was higher and nutrients were growth-limiting. Examining the simulation results also helped us identify feedbacks and interactions between different processes. For example, we identified a strong amplifying feedback between warming and rising CO_2, where warming enhanced decomposition and nutrient availability while rising CO_2 drove fertilization and improved water use efficiency. Because both nutrients and water were becoming more available across the catchment, the impact of both temperature and CO_2 increases on vegetation growth together were much greater than the sum of the two effects modelled separately. The impacts of vegetation changes on catchment hydrology (via transpiration) were not always straightforward due to the competing effects of enhanced growth and increased water use efficiency.

Given our results showed that complex ecohydrologic dynamics were important for simulated catchment response under future climate scenarios, we tested the implications of common modelling simplifications:

1. Ignoring the effects of CO_2 on plant stomata and hence water use efficiency
2. Ignoring dynamic vegetation growth and nutrient cycling
3. Assuming heterogeneity in soil properties

We found that the RHESSys model could be simplified in these ways under current climate conditions without substantially impacting the simulation results. However, when we modelled future climate scenarios, the first two simplifications caused major discrepancies. For example, mean transpiration was overestimated (up to 29%, depending on the scenario) and mean flow was underestimated (up to 12%) when stomatal closure effects were removed from the model for future climate simulations. Ignoring dynamic vegetation growth caused underestimation of mean transpiration (up to 19%) and overestimation of mean flow (up to 16%). Leaf Area Index (indicating vegetation growth) was underestimated by up to 34% in this model version, relative to the full RHESSys model. These results show that, although model simplifications can often be justified by similar performance under historical conditions, more detailed process representation is likely to be important for future projections under climate change.

Keywords: *Ecohydrology, climate change, spatial heterogeneity, vegetation response, virtual catchment*

EXTENDED ABSTRACT ONLY

Systematic investigation of hydrological non-stationarity for robust hydrological modelling

[a]Zheng H, [a]Chiew FHS, [b]Guobin Fu and [c]Robertson DE

[a]CSIRO Land and Water, Black Mountain, Canberra
[b] CSIRO Land and Water, Private Bag 5, Wembley, WA 6913, Australia
[c]CSIRO Land and Water, Clayton, Melbourne
Email: Hongxing.zheng@csiro.au

Abstract: Hydrological non-stationarity is the shift in hydrological behaviour of a catchment in response to changes in climate conditions (e.g., prolonged drought) or catchment properties (e.g., land use and land cover changes). One of the most widely reported evidence of hydrological non-stationarity is the shift in the rainfall-runoff relationships at the annual scale. For example, in southeastern Australia, runoff coefficient or the relationship between annual rainfall and runoff has changed significantly in many catchments due to the 2007– 2009 Millennium drought. The non-stationarity of the hydrological system has imposed challenges in hydrological forecasting and projection where the hydrological model may fail to represent the hydrological processes of a catchment under considerable climatic or physical changes due to deficiencies in model structure or model parameterization.

Research studies continue to investigate the underlying mechanisms of hydrological non-stationarity and are attempting to improve hydrological model conceptualization and parameterization for more robust catchment modelling. The drivers of hydrological non-stationarity investigated include changes in rainfall typology, connection between surface water and groundwater, sub-surface evapotranspiration process and changes in vegetation characteristic and behavior. However, there remains a lack of knowledge in the determinants or thresholds that trigger hydrological non-stationarity.

This paper presents a systematic investigation of hydrological non-stationarity for catchments in southeastern Australia, using the pre drought, Millennium drought and post drought data. Temporal variations (e.g., trends and abrupt changes) of model performance measured by different hydrological variables (e.g., total runoff, baseflow, evapotranspiration) and metrics (e.g., bias, NSE) are investigated to better understand the non-stationarities of the dominant hydrological components and processes. The temporal variations of hydrological model parameters are also investigated with special consideration of the connections between the sensitive parameters and the dominant climate characteristics (e.g., annual rainfall, aridity index) and catchment properties (e.g., vegetation index). The results indicate that the non-stationarities are more significant in low flows rather than in high flow. The cumulative effects of rainfall deficit are generally underestimated or not well reproduced by the hydrological models. The learnings here will help improve development of more robust hydrological modelling in catchments experiencing substantial climate or land cover changes.

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Keywords: *Hydrologic non-stationarity, hydrological modelling, hydrological processes, multi-timescale*

Multi-frequency retrieval of soil moisture profile

Foad Brakhasi [a], **Jeffrey P. Walker**[a], **Xiaoji Shen**[a], **Nan Ye** [a], **Xiaoling Wu**[a], **In-Young Yeo**[b], **Nithyapriya Boopathi**[a,c] **and Richa Prajapati** [a,c]

[a] *Department of Civil Engineering, Monash University, Clayton, Australia*
[b] *School of Engineering, The University of Newcastle, Callaghan, Australia*
[c] *IITB-Monash Research Academy, Mumbai, India*
Email: Foad.Brakhasi@monash.edu

Abstract: Better understanding of the soil moisture profile leads to better prediction of floods, droughts and agricultural productivity, and a better management of water consumption. Moreover, soil moisture in the top 20 cm or more of the soil limits the plants photosynthetic activity and transpiration. Apart from the use of data assimilation techniques and/or employing P-band radar observation for bulk root zone soil moisture estimation, the main focus of the remote sensing community has been on retrieving top 5 cm surface soil moisture. Further, passive microwave remote sensing technology has been identified as the most promising approach for soil moisture observation globally, with current satellites directly dedicated to the monitoring of soil moisture operating at L-band (1.4GHz; 5cm sensing depth). In contrast, P-band (750MHz) is expected to be sensitive to a much deeper layer of soil moisture (~10-cm) which can potentially provide insights into the depth variation of soil moisture. Therefore, it is postulated that by combining L-band and P-band radiometer data that soil moisture information, including variation with depth, may be retrieved beyond the penetration depth.

An inversion scheme including the stratified coherent forward model approach for retrieving the soil moisture profile using combined L-band and P-band passive microwave observations under flat and bare soil was proposed and tested. Different functions including a linear (L), exponential (Exp), second-order polynomial (Pn2), and third-order polynomial (Pn3) were considered as options to represent a typical soil moisture profile. An iterative optimization scheme using the particle swarm intelligence (PSO) algorithm was employed to minimize the cost function and retrieve the desired soil moisture profile parameter of interest. Field data from April 2019 were used, including soil moisture and temperature profiles to 60 cm depth in 5 cm increments covering soil moisture from 0 to 0.20 cm^3/cm^3, and brightness temperature at L-band and P-band passive microwave observation at 40° incidence angle and H/V polarization. This data is from a comprehensive tower-based experiment site established at Cora Lynn, Melbourne, Australia. Ten soil moisture profiles from different days at 6 AM form the period of observation selected for retrieval from simulated and experimental brightness temperature. In the synthetic study, different levels of low (high) noise up to 1 (4) Kelvin were imposed on the simulated brightness temperature. The soil moisture profile was retrieved under low (high) noise scenario as being L 33 cm (33 cm), Exp 35 cm (27 cm), Pn2 51cm (45 cm), and Pn3 49 cm (46 cm). Based on the synthetic study, the second-order polynomial was selected as the best function representing the soil moisture profile with the lowest RMSE and highest retrieval depth with acceptable error. Applying the model to observed brightness temperature from the tower for the ten soil moisture profiles the RMSE was 0.03, 0.05, and 0.046 m^3/m^3 in the 0-5 cm, 20-25 cm, and 55-60 cm depths of the profile respectively.

Keywords: *Soil moisture profile, mathematical function, P-band, passive microwave, coherent model*

EXTENDED ABSTRACT ONLY

High resolution soil moisture model calibration using Markov Chain Monte Carlo algorithm

Dejun Cai [a] **and Luigi J. Renzullo** [a]

[a] *Fenner School of Environment and Society and Institute for Water Futures, the Australian National University, Canberra, 2601, Australia*
Email: dejun.cai@anu.edu.au

Abstract: Accurate estimation of soil moisture (SM) informs water resources management, agricultural planning and weather prediction. A data assimilation system uses satellite data from Soil Moisture Active Passive (SMAP) to optimally correct SM estimates from Antecedent Precipitation Index (API) model towards satellite observations. This study investigated the use of SMAP data in model calibration as another model improvement approach by identifying parameter values that help API model simulate behaviour of SM variations more realistically. A Bayesian statistical algorithm, Markov Chain Monte Carlo (MCMC) algorithm, was designed and implemented at 13 study sites in Australia to calibrate two parameters characterising SM memory in API model against SMAP data. Parameter distributions obtained from MCMC were used to produce a collection of possible calibrated model states (ensemble). Uncalibrated estimates, estimates with MCMC calibration and with assimilation were evaluated by linear correlation with in-situ cosmic-ray SM measurements (CosmOz network) within a 5-year experiment period. Results showed that calibrated parameter values showed clear heterogeneity across different sites and their spatial variations were linked to site-specific aridity conditions and seasonal rainfall patterns. MCMC calibration improved model performance by as much as 105% for 11 sites. Data assimilation generally attained better performance than calibration, but there were two sites where some members in the calibrated ensemble improved SM estimation more evidently. These results demonstrated merits of site-specific model calibration and highlighted the prospect of complementing data assimilation with MCMC-based calibration. This would help maximise model accuracy for SM estimation and ultimately support various hydrological, agricultural and meteorological applications.

Keywords*:* *Satellite soil moisture, model calibration, Markov Chain Monte Carlo algorithm, ensemble prediction, data assimilation*

Assimilating satellite-based flood extents into flood inundation models for improved forecasts

Antara Dasgupta[a,b,c], Renaud Hostache[d], RAAJ Ramsankaran[c], Stefania Grimaldi[c], Guy Schumann[e,f], Valentijn Pauwels[c] and Jeffrey P. Walker[c]

[a]IITB-Monash Research Academy, [b]IIT Bombay, [c]Monash University, [d]Luxembourg Institute of Science and Technology, [e]RSS-Hydro Sarl-S, [f]University of Bristol
Email: jeff.walker@monash.edu

Abstract: The climate emergency has exacerbated catastrophic flooding and put an unprecedented number of people at risk. Accurate information on flood inundation is therefore critical to bolster preparedness and reduce flood related losses. Satellite-based Synthetic Aperture Radar (SAR) sensors with all-day/all-weather imaging capabilities, provide frequent real world observations of flooded areas, which can be leveraged to improve the forecasting capabilities of numerical flood inundation models. Studies have shown that integrating independent flood extent observations from satellites with physical models, help keep the forecasts on track for longer lead times. However, sensitivity of the assimilation likelihood function to slight changes in the flood extents was a major challenge. Since new-generation high-resolution SAR sensors typically provide partial coverage of the channel and the floodplains, objectively choosing optimal observations to maximize forecast improvements is also vital. Therefore, cost-effective acquisition planning requires a keen understanding of the influence of location, timing, and frequency of satellite-based flood extent observations on flood extent assimilation and eventually the forecast skill. The present study first proposed a novel assimilation likelihood function based on mutual information to improve the uptake of information from SAR-based flood extents and verified its potential through identical twin experiments for the 2011 flood in the Clarence Catchment, NSW. The truth simulation used observed inflows, calibrated parameters, and LiDAR topography, while the open loop considered erroneous inflows with everything else remaining exactly the same. Synthetic SAR images generated based on empirical error estimates from COSMO-SkyMed SAR images available for the event, were subsequently converted to probabilistic flood extents and assimilated into the two-dimensional hydraulic model LISFLOOD-FP at 90m grid resolution. Synthetic observations with full catchment coverage were first used to develop the new likelihood function based on particle filtering, where the proposed flood extent assimilation algorithm performed equivalently or better than the state-of-the-art. Three catchment sub-regions, delineated by flow distances based on reach flow behavior and catchment morphology, were then chosen to assimilate partial synthetic observations, to identify the impact of observation acquisition parameters and design a targeted observation strategy for the catchment. Results showed that forecast skill was more sensitive to observation coverage and timing with respect to the flood wave arrival time than frequency, contrary to the findings of previous studies. Flood inundation forecasts can thus be substantially improved by optimizing image acquisition parameters for assimilation, providing more reliable information for actionable decision-making during emergencies.

Keywords: *Earth observation, flood inundation modelling, data assimilation, particle filters, mutual information*

Remotely sensed crop biomass model over wheat cropping field for assimilating Sentinel-2 imagery into a crop yield prediction model

Shirui Hao[a], Dongryeol Ryu[a], Andrew W. Western[a], Eileen Perry[b,a], Heye Bogena[c] and Harrie Jan Hendricks Franssen[c]

[a] *Department of Infrastructure Engineering, Faculty of Engineering and Information Technology, The University of Melbourne*
[b] *Agriculture Victoria, Department of Jobs, Precincts and Regions*
[c] *Institute of Bio- and Geosciences, Agrosphere Institute (IBG-3), Forschungszentrum Jülich*
Email: shiruih@student.unimelb.edu.au

Abstract: Process-based crop models such as APSIM are usually used as the predictive tool to provide timely and reliable yield prediction and help design efficient management practices to boost crop production. However, a recent review work (Hao et al., 2021) found that the performance of APSIM-Wheat yield prediction is negatively affected by poor calibration, extreme stresses of heat, frost, water, and nitrogen. Remote sensing data can provide vegetation information at high spatial and temporal resolutions. This information can be used to improve in-season crop growth modelling and eventually yield prediction by assimilating the remote sensing data. Observation operator, which is a model translating remotely sensed data into equivalent model state variables, is one of the key components of the data assimilation system. This work developed a nonlinear observation operator to link Sentinel-2 retrieved vegetation indices (VI) with the green leaf area index (GLAI) simulated by the APSIM-Wheat Next Generation (APSIMX-Wheat) model (Holzworth et al., 2018).

In this work, we used distributed yield data from a 2019 winter-wheat 106 ha field located in the north-western Victoria, Australia. Seven regions of interest (ROIs) with yields varying between 3 and 8 t/ha were selected to calibrate APSIMX-Wheat. Then the LOcally WEighted Scatterplot Smoothing method (LOWESS) was employed to establish a model predicting APSIMX GLAI values using Sentinel-2 VIs (**Table *1***) over the growing season. Separate observation operators were developed for pre- and post- modelled GLAI peak time since the regression lines showed very different trends for these two time periods. Root mean squared error (RMSE) and normalised RMSE (NRMSE) between LOWESS predicted and modelled GLAI were computed to assess the fit of the LOWESS curves (**Table *1***). In general, VIs computed from red edge and NIR bands show the smallest RMSE and NRMSE, implying that these are the best candidates for observation operators with APSIMX-Wheat. While VIs using red and NIR bands show the largest error values. NDVI-based VIs tend to saturate at moderate to high modelled GLAI, which is disadvantageous.

Table 1. Multispectral vegetation indices investigated in this study (α, a, b, c used in calculating WDRVI and GLAI follow values proposed by Nguy-Robertson et al. (2014))

Vegetation index	Equation	Resolution	Pre-peak		Post-peak	
			RMSE	NRMSE	RMSE	NRMSE
Green WDRVI	$(\alpha \cdot NIR - Green)/(\alpha \cdot NIR + Green) + (1-\alpha)/(1+\alpha)$	10m	0.72	37.9%	0.81	20.1%
Red WDRVI	$(\alpha \cdot NIR - Red)/(\alpha \cdot NIR + Red) + (1-\alpha)/(1+\alpha)$	10m	0.91	47.7%	0.83	20.7%
Red edge WDRVI	$(\alpha \cdot NIR - Red\ edge)/(\alpha \cdot NIR + Red\ edge) + (1-\alpha)/(1+\alpha)$	20m	0.58	30.4%	0.80	19.9%
Green GLAI	$a \cdot Green\ WDRVI^2 + b \cdot Green\ WDRVI + c$	10m	0.71	37.3%	0.73	18.3%
Red edge GLAI	$a \cdot Red\ edge\ WDRVI^2 + b \cdot Red\ edge\ WDRVI + c$	20m	0.59	31.1%	0.78	19.3%
Green CI	$(NIR/Green) - 1$	20m	0.7	37.0%	0.78	19.5%
Red edge CI	$(NIR/Red\ edge) - 1$	20m	0.58	30.7%	0.76	18.9%
Green NDVI	$(NIR - Green)/(NIR + Green)$	20m	0.96	50.5%	1.12	27.8%
Red NDVI	$(NIR - Red)/(NIR + Red)$	20m	1.09	57.5%	1.1	27.4%
Red edge NDVI	$(NIR - Red\ edge)/(NIR + Red\ edge)$	20m	0.57	29.8%	0.86	21.4%

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Keywords: *Observation operator, Sentinel-2, vegetation indices, APSIM Next Generation, wheat*

P-band microwave remote sensing for improved soil moisture retrieval

Xiaoji Shen , Jeffrey P. Walker, Nan Ye and Xiaoling Wu

Department of Civil Engineering, Monash University, Clayton, Victoria
Email: xiaoji.shen@monash.edu

Abstract: Soil moisture is an excellent indicator of climate change, controlling various processes in the water, energy, and carbon exchanges between the atmosphere and the land surface. There are two L-band (~21 cm wavelength / 1.4 GHz) space missions currently operating for observing global soil moisture: ESA's (European Space Agency) Soil Moisture and Ocean Salinity (SMOS) satellite and NASA's (National Aeronautics and Space Administration) Soil Moisture Active Passive (SMAP) satellite. However, these measurements are limited to a relatively shallow moisture retrieval depth, which is commonly held to be within the top 5 cm at L-band, hindering widespread applications in hydrological and weather forecast, flood and drought prediction, and climate change. It is a widely held understanding that a longer waveband should have a deeper moisture retrieval depth and reduced impact from surface roughness and vegetation (Ulaby et al., 1986), resulting in a more useful contributing depth and an overall higher retrieval accuracy of soil moisture. However, this has not been demonstrated at P-band (~40 cm wavelength / 0.75 GHz) due to the lack of observations.

This research has established a comprehensive tower-based experiment site in Australia and has collected a long timeseries dataset (2017-2021) of tower-based P- and L-band radiometric observations along with in-situ soil moisture measurements. Based upon this dataset, P-band has been demonstrated to have a deeper moisture retrieval depth (~7 cm) than L-band (~5 cm), with the potential to achieve depths of more than 10 cm for frequencies below 0.5 GHz. The tau-omega model was also evaluated over bare and wheat-covered flat and periodic soil surfaces at P- and L-band. Results showed that P-band retrieval accuracy was relatively unaffected by periodic roughness compared to flat surfaces for bare or wheat-covered soil, with an RMSE in the soil moisture retrieval of 0.01-0.03 m^3/m^3. Conversely, a considerable difference in soil moisture retrieval accuracy was observed for L-band observations of bare soil, with the RMSE being 0.02 m^3/m^3 over flat soil and 0.03-0.04 m^3/m^3 over periodic rough soil. In addition, the reduced vegetation impact at P-band was confirmed by undertaking soil moisture retrieval without considering vegetation effects, with the RMSE being 0.03 m^3/m^3 for P-band and 0.06 m^3/m^3 for L-band.

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Keywords: *P-band, passive microwave, moisture retrieval depth, surface roughness, vegetation impact*

Soil moisture retrieval from multi-angular P-band radiometer observations

Xiaoling Wu [a], **Jeff Walker** [a] **and Nan Ye** [a]

[a] *Department of Civil Engineering, Monash University, 3800, Australia*
Email: xiaoling.wu@monash.edu

Abstract: Economic, social and environmental planning for a water-limited future requires a capacity to provide information on soil moisture content in a way that is useful for such applications. Over the past three decades there have been numerous soil moisture remote sensing studies using visible, thermal-infrared (surface temperature) and microwave (passive and active) electromagnetic radiation. Of these, L-band microwave has proven to be the most promising approach due to its all-weather capability and direct relationship with soil moisture through the soil dielectric constant. Timely soil moisture information on near-surface layer is critical to improve water management for food production in the face of extreme climate variability. However, current satellite technologies are limited to the top ~5cm layer of soil using an L-band radiometer (1.4 GHz, 21cm).

Consequently, this study will demonstrate that P-band (750 MHz, 40 cm) radiometer observations will not only provide soil moisture information on a soil layer thickness that more closely relates to that affecting crop and pasture growth, but that it will produce greater spatial coverage with improved accuracy to that from L-band. Data for this study has been collected from the P-band Radiometer Inferred Soil Moisture (PRISM) field campaign in Yanco NSW during March 2021 (Figure 1). The overall objective of PRISM was to develop algorithms/techniques to demonstrate that top ~15cm layer of soil moisture can be remotely sensed using a new state-of-art P-band radiometer capability. A total of nine P-band flights were conducted during the campaign, with concurrent ground observations of soil moisture and ancillary data for a diverse range of conditions. P-band data were collected at different incidence angles (15˚ and 45˚) at 200m resolution over an area of ~3km x 20km. An example of P-band observations and the retrieved soil moisture is also shown in Figure 1.

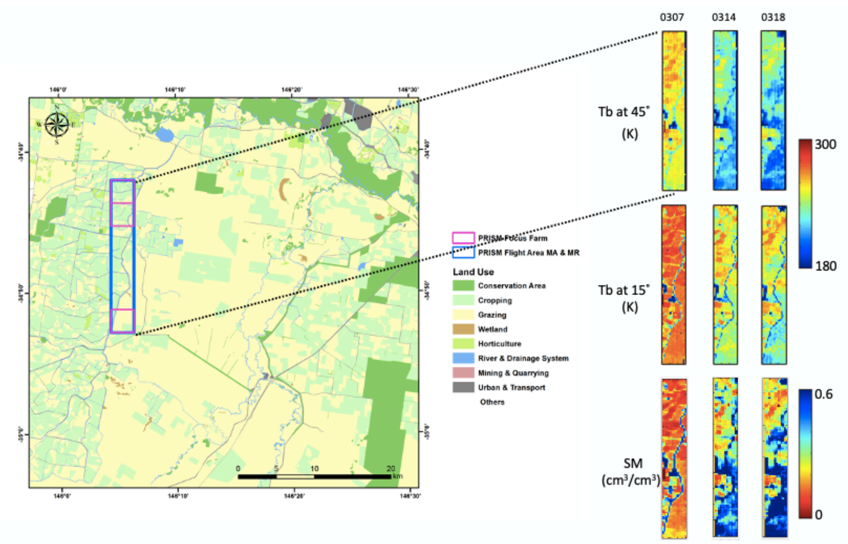

Figure 1. PRISM study area at Yanco NSW: blue represents P-band flight area, while red indicates the ground sampling areas. Also shown are the P-band brightness temperature over the 3km x 20 km area at *h*-pol at 45˚ and 15˚ respectively, together with the retrieved soil moisture. Data shown here were collected on 7th, 14th and 18th of March, 2021.

Soil moisture data were retrieved through *tau-omega* model using the multi-angular P-band data. Reference soil moisture have been collected using a hand-held instrument during ground sampling and were resampled to 200m grid. Future improvement involves the use of more accurate input parameters during retrieval, including the spatial map of vegetation water content and surface temperature, and the investigation on the impact from land cover types.

Keywords: *P-band radiometer, PRISM, soil moisture retrieval, multi-angle*

Continental scale downscaling of AWRA-L analysed soil moisture using random forest regression

Y. Yu [a], **L.J. Renzullo** [a] **and S. Tian** [a]

[a] *Fenner School of Environment & Society, The Australian National University, Australian Capital Territory*
Email: u6726739@anu.edu.au

Abstract: The Australian Water Resource Assessment Landscape (AWRA-L) model as used by the Bureau of Meteorology (BoM) provides daily continental scale soil moisture (SM) estimates (among other landscape water variables) at ~5-km resolution. At such a coarse scale these data cannot represent the high spatiotemporal variability of SM across heterogeneous land surfaces. Downscaling of coarse SM products based on machine learning (ML) has become increasingly popular due to its robust predictions and potential for large-scale applications. As a first step towards high-resolution daily Australia-wide SM estimation, a downscaling framework was developed to generate monthly SM with 500-m spatial resolution using analysed SM from AWRA-L and multisource geospatial predictors in random forest (RF) regression. Candidate predictors include digital elevation model (DEM), soil properties from the Australian soil and landscape grids, and several retrievals from the MODerate-resolution Imaging Spectroradiometer (MODIS). Ten experiments were conducted to decide the best combination of predictors. In the chosen model, DEM and available water capacity (AWC) were consistently identified as the most important predictors based on the ranking of variable importance.

The downscaled SM shows greatly enhanced spatial details at the local scale while maintaining consistent patterns with AWRA-L analysis at the continental scale. Validations against in-situ measurement networks using Pearson correlation coefficient (R) show that there is very little difference in the performance between the downscaled and AWRA-L SM. Average R values for the downscaled SM against CosmOz, OzFlux and OzNet were 0.87, 0.68 and 0.75, respectively, while the original AWRA-L SM average R were 0.86, 0.68 and 0.76, respectively. Furthermore, the time series comparison based on a wetness unit shows that the downscaled SM can well catch up the fluctuations of in-situ SM. In general, this study explores the potential of ML approach for the SM downscaling applications at the continental scale. It could be a promising direction to exploit the modelling capability of integrating multisource geospatial data including satellite retrievals, land surface models (LSM) and interpolated ground observation data. Future directions should concentrate on integrating this approach into an operational framework with a daily frequency. Exploration of the relationships between SM and auxiliaries under difference scales would be essential, in order to better understand the dominant physical controls on spatial variability of SM.

Keywords: *Soil moisture, Australian Water Resource Assessment Landscape (AWRA-L) model, downscaling, machine learning, random forest*

Modelling farm-scale floodplain harvesting diversions in northern Murray-Darling Basin

R. Beecham[a], **M. Sivkova**[a] **and L. Holz**[b]

[a]Knowledge Division, [b]Operations Division, Water Group,
Department of Planning, Industry and Environment,
Parramatta, 2150, NSW Australia
Email: Richard.Beecham@dpie.nsw.gov.au

Abstract: Estimating the amount of water diverted from the floodplains in northern inland NSW for consumptive use has been the focus of a large modelling effort by Department of Planning Industry and Environment. This work is as part of a larger effort by the department to implement a policy to regulate floodplain harvesting. Further upgrades are planned as more data are collected and methods improved.

The northern NSW tributaries of the Murray-Darling Basin exist in a summer dominant rainfall region subjected to multi-year periods of low rainfall. Rainfall is highest in the headwaters to the east, decreasing to the west, whereas potential evapotranspiration increases to the west. The tributaries that flow from the east - the Dumaresq-Macintyre, Gwydir, Namoi and Macquarie, flow west to north-west to join Barwon-Darling River which then flows into the Menindee Lakes. These tributaries are characterised by large public headwater storages below the high runoff yielding catchments, grading to floodplains with effluent channels and include Wetlands of International Importance under the Ramsar Convention.

The fertile alluvial soils below the headwater storages have led to an economically significant irrigation industry developing. Climate conditions have resulted in a farm operational model reliant on large private on-farm storages. Water access in these tributaries is managed through statutory plans, which share access to the water in the headwater storages and in-channel unregulated water. The water diverted from floodplains is not currently regulated, leading to their growth over time. A policy to regulate diversions from the floodplain has been agreed, and the modelling is being used to support implementing this policy.

This required substantively upgrading our models. Whereas pre-existing water planning models developed using IQQM or Source software aggregated multiple individual farms to a single computational point, we now had to model each farm individually and the water balance on each farm in greater detail, greatly increasing model complexity. An unprecedented level of data collection and analysis and method development supported this upgrade, to ensure the results were as robust as possible. The modelling effort was subjected to regular stakeholder consultation, detailed reporting and a comprehensive independent expert peer review.

Data collected included detailed farm surveys of infrastructure, cropping and diversion history, supplemented by traditional hydroclimatic databases, remote sensing imagery, floodplain hydraulic models, and published data. Despite this data effort, a key data gap was the component we were trying to estimate – volumes of water diverted from the floodplain. We used a multi-scale approach based on water balance principles at: individual farm scale, river reach scale and whole of river system scale to estimate floodplain diversions results that were robust, albeit with higher levels of uncertainty than other water balance components.

Future improvements to reducing uncertainty in water balance is planned. This includes upgrading methods to quantify the hydrological fate of different volumes of water on the floodplain, and recalibrating floodplain harvesting diversions using metered data proposed to be collected under the policy.

Keywords: *Floodplain harvesting, farm models, river system model, diversion limits*

Water security in the face of risky weather

R. S. Blakers, N. Loonat, D. Dutta, and R. Beecham

Water Group, Department of Planning, Industry and Environment, New South Wales (NSW), Australia
Email: rachel.blakers@dpie.nsw.gov.au

Abstract: An understanding of climate risks to water security is essential to plan and manage the future needs of communities, the environment, and industry. This paper presents a method that combines climate, rainfall-runoff, and river system models to evaluate the risks associated with climate variability and climate change. It suggests a way forward to address some of the shortcomings in existing approaches and makes recommendations to address challenges that still persist.

The assessment of the combined effects of long-term climate variability and climate change can reduce vulnerability and enhance community resilience to future climate-related adverse impacts. Prediction of water availability, at least in some probabilistic or plausible projection sense, can be achieved through hydrological models. The Department of Planning Industry and Environment-Water (DPIE-Water) holds a suite of rainfall-runoff and river-system models encompassing the majority of NSW catchments. There are a number of challenges that restrict its application to climate risk assessment. The models were calibrated using an instrumental climate record spanning the late 1800s to the present. This period is insufficient to understand long-term climate variability and the occurrence and frequency of extreme events. A second challenge is to understand the potential future impacts of anthropogenic climate change. The NARCliM project provides high-resolution climate change projections across NSW derived from dynamically downscaled general circulation models (https://climatechange.environment.nsw.gov.au). Despite being the state of the art, the physically-based climate models do not preserve local rainfall characteristics with sufficient fidelity to be used directly in DPIE-Water's rainfall-runoff models, and they struggle to represent natural multi-year climate variability. This study addressed these issues by coupling stochastic climate models with paleoclimate information, information on climate drivers, and factoring of the NARCliM projections. The stochastic models were developed in collaboration with the Adelaide University and the University of Newcastle. The scale of the project was ambitious, involving the generation of 10,000 years (or more) of stochastic rainfall, evaporation, and temperature data for around 2,000 weather stations in NSW and connected watersheds. When combined with rainfall-runoff and river system models, the stochastic sequences allow assessment of long-term hydrological variability and the occurrence of extreme events, while the NARCliM projections provide insights into how climate change may impact water supply schemes (Figure 1).

A key lesson learnt from the project was that the quality assurance of synthetic climate datasets must consider their performance within the hydrological models themselves. An independent expert panel has reviewed DPIE-Water's climate risk method and made several recommendations for future work. Two priority areas of current development are to address non-stationarity in the historical record and to establish a community of practice to share innovations in the science of climate risk. DPIE-Water is currently working towards making the stochastic climate datasets available in the public domain.

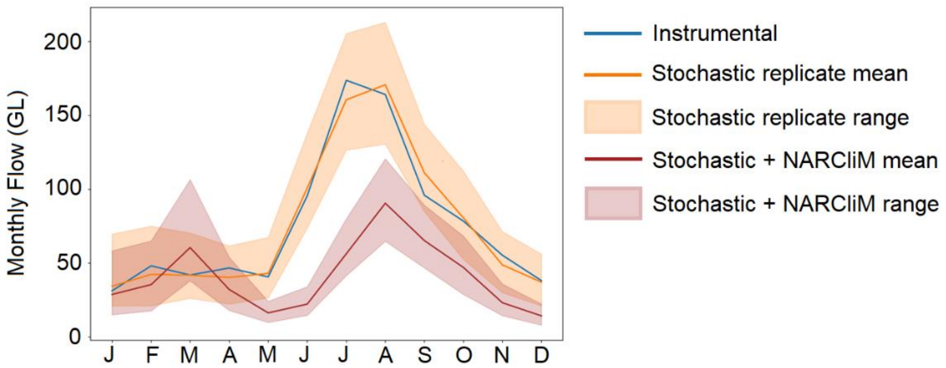

Figure 1. Comparison of simulated monthly inflow to Burrendong Dam using the 130-year instrumental climate record, an ensemble of 76 stochastic climate replicates, and NARCliM factored stochastic replicates.

Keywords: *Climate risk, water supply security, stochastic climate models, river system modelling*

Applications of river system models to strategic planning for water security

D. Dutta[a], A. Trim[a], J. Simpson[a], R. Beecham[a], M. Simons[b], J. Kinley[b], D. Harris[b] and A. Craig[b]

[a]*Knowledge Division,* [b]*Strategy Division, Water Group, Department of Planning, Industry and Environment NSW, Australia*
Email: dushmanta.dutta@dpie.nsw.gov.au

Abstract: The NSW Department of Planning, Industry and Environment (DPIE) has been developing regional water strategies across NSW to enhance the management of water to improve water security. The strategies aim to determine how much water a region needs to meet future demand, and identify challenges and choices involved in meeting those needs. The strategies set out actions to improve the resilience of regional water resources for towns and communities, the environment, Aboriginal communities and industry.

In the development of the strategies, a risk-based approach has been applied to assess hydrologic, economic and ecological implications and outcomes for a range of potential water supply/demand options. This approach is aimed at defining risks to essential water supply and the regional economy from climate variability and drought under current levels of water supply infrastructure, and potential for mitigation of this risk via augmentation of the water supply infrastructure and/or operational changes in a river valley.

Hydrologic and river system modelling have been undertaken in more than 20 regulated and unregulated river system across NSW and several upstream rivers including the Snowy River, upstream Queensland tributaries of the Barwon-Darling River and Victorian tributaries of the Murray River to support the assessments. In every region, river system modelling has been implemented in three stages: 1) basecase modelling to inform the draft strategies, 2) basecase modelling to support the development of economic basecase, 3) options modelling to inform the final strategies. Three sets of climate data are used in each stage of modelling that included about 130-year of daily recorder data, 10,000 years of stochastic climate data and 10,000 years of stochastic data with climate projection using NARCliM 1.0 (Figure 1).

The paper presents the overall modelling methodology implemented across various river systems with examples describing two costal river systems: Richmond River system in Far North Coast and Bega River System in South Coast of NSW. Both of these river systems are managed by a combination of regulated and unregulated water sharing plans. eWater Source modelling platform was used to develop current-condition basecase river system models for these two river systems, which included the key water demand models including local water utilities and irrigators. Some of the key results of the modelling are presented and findings are discussed in this presentation.

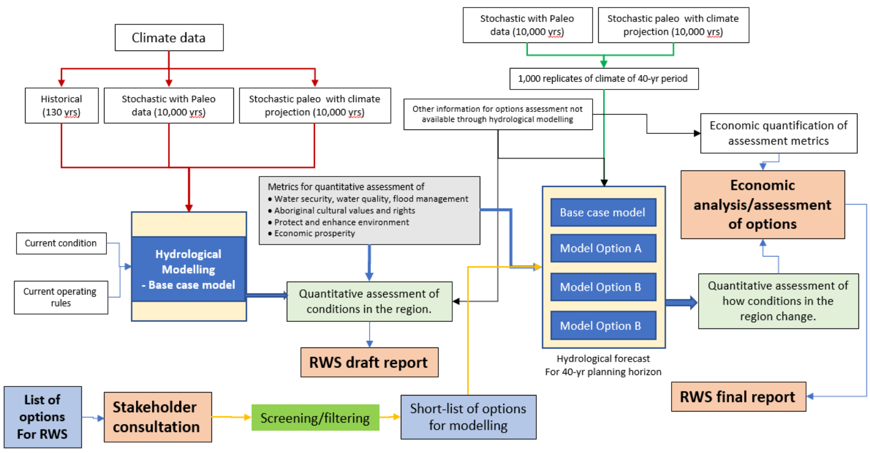

Figure 1. Flowchart showing the overall hydrological modelling approach to inform RWS development

Keywords: *River system modelling, NSW Regional Water Strategy, stochastic climate data, NARCliM*

Comparing suitability of two rainfall runoff models in a Victorian ephemeral catchment

E Guthrie [a], **P Jordan** [a], **K Austin** [a], **K Szabo** [a] **and R Pinto** [a]
[a] *Hydrology and Risk Consulting (HARC), 3130 Victoria, Australia*
Email: ella.guthrie@harc.com.au

Abstract: The Werribee basin contains a series of rivers and ephemeral creeks that are typically flow-stressed, responding quickly to rainfall events and experiencing prolonged periods of very low or no flow (DELWP, 2018), making it difficult to fit a rainfall runoff model. This study compares the performance of two rainfall runoff models, Sacramento and GR4J with loss, in fitting to gauged streamflow for a typical site in the basin, the Werribee River at Ballan, over the period of March 1973 to September 2018.

Both models were calibrated using eWater Source, initially optimised using the Shuffled Complex Evolution (SCE) algorithm, with the Nash Sutcliffe Efficiency (NSE) Daily and bias penalty objective function. Both models were then optimised again an alternative calibration approach to specifically match this flow regime. The Sacramento model was calibrated in stages, whereby parameters were grouped into like function in order to account for parameter interaction (HydroTechnology, 1995). This process involved calibrating in stages, using the NSE objective function and then optimising low flow parameters using SDEB. Further optimisation of the GR4J model involved adjusting production and routing store capacity to match magnitude and timing of flows, with the aim of achieving a good global fit, focusing on matching the shape of the recession curve. As the GR4J model required further reductions in low flow magnitude, a loss function was used to improve recession curve fit.

Table 1. Calibration Results Werribee River at Ballan

	GR4J Cal 1	GR4J Cal 2	Sac Cal 1	Sac Cal 2
R^2	0.79	0.79	0.73	0.75
Vol. Bias (%)	-0.23	24.66	4.01	10.77
NSE Log Daily	0.57	0.65	0.45	0.45
NSE Monthly	0.68	0.59	0.84	0.895
SDEB	34855	21029	18242	21145

In applying the autocalibration method, both Sacramento and GR4J models are limited in their ability to reproduce flows with both magnitude and timing accuracy. Statistically, GR4J performs best, but has greater variance in flow peaks, whereas Sacramento produces a timeseries that matches seasonality, and the characteristic low flows of the gauged data, but can underestimate peaks and produce a flatter than desired recession curve. For both cases, the flow duration curves are notably improved with the alternative method, indicating that manual fitting of model parameters is able to achieve a closer estimate of the baseflow. This process was replicated over several sites in the Werribee basin with good data availability, and results from the alternative calibration method for both models yielded flow that was better able to replicate the pattern of gauged flow, while improving the coefficient of determination (R^2), NSE Log Daily and Monthly, as well as flow duration curves.

Both models produce good results over the calibration period, GR4J offers better global fit while Sacramento offers more robust results for catchments with characteristic ephemerality. Using a loss function can improve goodness of fit in catchments where there is a steep flow recession curve, but this is subject to user bias and is a risk of overfitting to the calibration period. This is acceptable where the modelled flow is used for infilling a streamflow series, or modelled for stationary climactic conditions. When using the model to forecast future flow, or as a proxy for future climate scenarios, using a manually calibrated global loss function may be unsuitable. These methods also pose limitations in predicting post drought catchment response, due to potential changes in catchment behaviour under changing climactic conditions (Fowler et al., 2016).

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Keywords: *Rainfall-runoff modelling, manual calibration, GR4J, Sacramento*

Modelling in-stream nutrient processes under different streamflow regimes

Donghwan Kim [a], **Melanie E. Roberts** [a,b], **Jing Lu** [a], **David T. Roberts** [c], **David P. Hamilton** [a]

[a] *Australian Rivers Institute, Griffith University, Nathan, Queensland 4111*
[b] *School of Environment and Science, Griffith University, Nathan, Queensland 4111*
[c] *Queensland Bulk Water Supply Authority (Seqwater), Brisbane, Queensland 4000*
Email: donghwan.kim@griffithuni.edu.au

Abstract: Numerical modelling using coupled hydrodynamic-ecological models is a valuable tool to support water quality management of streams and rivers. It provides a basis for understanding the complex physical and biochemical processes in the study area and allows for the simulation of management actions prior to implementation. The results of these models are critically influenced by the interaction between external (boundary) conditions and internal fluxes, which in streams and rivers will vary with flow rates and residence time. Here we explore the relative contributions of boundary conditions and internal fluxes on downstream water quality in the mid-Brisbane River under different flow regimes and consider how partitioning these flow regimes affects model performance.

Our study area is 61 km of the Brisbane River between the Wivenhoe Dam outflow upstream and the Mt Crosby Weir drinking water intake downstream, which we refer to as the mid-Brisbane River. Downstream of the Mt Crosby Weir, the mid-Brisbane River flows into Moreton Bay, which is of significant ecological value. Located in a subtropical region, the mid-Brisbane River is subject to seasonal stormflows and a consistent baseflow determined mostly by the regulated dam outflow. In the summer rainy season, the largest tributary, Lockyer Creek, can be a major water source and is subject to large floods. Two sewage treatment plants also discharge within the mid-Brisbane River.

We collected bathymetry, meteorology, flow, surface water elevation, and water quality data from 2012 to 2019 from Queensland government, Bureau of Meteorology and Seqwater sources. Using these input data, the two-dimensional hydrodynamic and water quality model CE-QUAL-W2 (ver.4.2) was used to simulate flow and nutrient concentrations within the mid-Brisbane River. Eleven biogeochemical kinetic parameters relevant to nitrogen and phosphorus processing within the river were modified in 150 model runs that randomly selected input values within a range of 20 to 500% of each model default value. We then used statistical analyses, i.e., root mean square error, R^2, Nash-Sutcliffe Efficiency, and Percent Bias, to select best overall model fit to the model state variables from the 150 runs, whilst retaining the other model outputs to indicate a level of model uncertainty.

Ammonium (NH_4-N) and nitrate/nitrite (NO_x-N) concentrations were highly variable under different streamflow conditions, compared with other nutrient forms. All nutrient forms were found to be boundary-driven under stormflow conditions (i.e., short residence time of < 3 days in the model domain), with concentrations increasing slightly or showing no change along the river. Under baseflow conditions, and hence longer residence times (> 12 days), however, NH_4-N and NO_x-N concentrations decreased along the river while total nitrogen, total phosphorus, and orthophosphate concentrations were relatively constant. The longitudinal changes in NH_4-N and NO_x-N concentrations during baseflow were most sensitive to nitrification and denitrification rate parameters.

The observed longitudinal changes in nutrient concentrations were generally simulated well under both stormflow (largely dependent on the boundary settings) and baseflow (greater dependence biochemical parameter settings). River modelling should carefully consider the effect of residence time on the outputs that are influenced by internal nutrient processes.

Keywords: *Water quality model, model calibration, residence time, subtropical stream, mid-Brisbane River*

Temporal convolutional network algorithm for streamflow predictions in a subtropical river

Y.L.Liu [a], **C.Deng** [b] **and H.Zhang** [b]

[a] *School of Information Technology and Electrical Engineering, The University of Queensland, Brisbane, Queensland,* [b] *School of Engineering and Built Environment, Griffith University, Gold Coast, Queensland*
Email: yilun.liu@uqconnect.edu.au

Abstract: Rainfall-runoff models have a high degree of uncertainty and stochasticity, and the relationship between them is non-linear. Conventional hydrology streamflow prediction models are mostly built for specific watersheds and specific prediction scales, which are poorly promoted and applied. Therefore, in some scenarios, data-driven machine learning predictive models are replacing traditional physical models. Long short-term memory (LSTM) network is a machine learning algorithm for predicting time series and has been applied in the field of streamflow prediction. Temporal convolutional network (TCN) is another machine learning algorithm that is gaining popularity in the field of time series forecasting. LSTM and TCN were implemented in this study to analyse the hourly streamflow prediction for the Nerang River at the Numinbah gauging site, and the predictive accuracy of the models on the test dataset was calculated based on the historical data of the study area. According to the results of the analysis, the TCN model achieved better performance for the hourly streamflow prediction with a coefficient of determination (R^2) of 0.9837 and Nash–Sutcliffe efficiency (NSE) of 0.9829 in the best scenario and the lag time for hourly streamflow generation is about three hours in the study area. Additionally, the maximum predicted lead time is six hours in the study area on the TCN model.

In summary, the accuracy of hourly streamflow prediction using the TCN algorithm is of a good level. Moreover, streamflow can be predicted for up to six hours. Finally, this study demonstrates that the novel TCN algorithm has enormous potential for solving streamflow prediction problems in comparison to the LSTM algorithm.

Keywords: *Hourly streamflow prediction, temporal convolutional network, long short-term memory network, machine learning, data-driven model*

Improving catchment runoff estimates by ameliorating the impacts of SILO pluviometer data discontinuities through expanding the SILO reference database

L. K. Stewart[a] **and S. J. Jeffrey**[b]

[a]*Paddock to Reef Program, Queensland Department of Resources, Australia*
[b]*Land Surface Sciences, Queensland Department of Environment and Science, Australia*

Abstract: Australian Bureau of Meteorology (BOM) pluviometer records are used to inform the SILO database of gridded Australian climate data (Jeffrey et al., 2001). The SILO gridded climate data values are generated using mathematical interpolation techniques to construct spatial grids and infill gaps in time series datasets. As such, discontinuities in the pluviometer record at a particular location, such as the initiation or cessation of a pluviometer have the potential to introduce a step change in the characteristics of interpolated rainfall estimates for nearby locations, with implications for modelled runoff and flow within catchment models.

We provide an example, relating to the Tully River catchment, North Queensland, Australia, where such discontinuities significantly impact the frequency distribution of rain-day-depth, the annual-averages of categorised rain-day-depths, and long-term trends in estimated rainfall at SILO grid-points. Secondly, we show that despite these discontinuities, runoff estimates were significantly improved with better spatial coverage of rainfall data.

The Tully River flow is modelled within the Paddock to Reef (P2R), Wet Tropics catchment model over the period July, 1986 to June, 2014 inclusive (McCloskey et al. 2021). Within the upper Tully River catchment area, rainfall observations commenced at the Sutties Creek pluviometer in 2001, and observations ceased at the Koombooloomba Dam pluviometer in 2011. In concert with the inception of the Sutties Creek pluviometer the annual average modelled flow of the Tully River post 2000 was reduced by 18.1%. We show the association of pluviometer inception with sudden changes in the frequencies of categorised, estimated rain-day-depths and average annual rainfall within categorised, estimated rain-day-depths at a nearby SILO grid-point (up to a 32% reduction). Similar results are associated with the cessation of the Koombooloomba Dam pluviometer.

The large magnitude of such changes is likely due to the upper Tully catchment being primarily represented by extremely mountainous terrain, where the orographic effect will be prevalent, and few pluviometers. Thus, the initiation or cessation of a pluviometer site can influence a wide area in the SILO spatial interpolation of observed rainfall values.

To examine the value of additional pluviometer data in ameliorating the impacts of pluviometer data, discontinuities, we assessed a new set of SILO gridded rainfall estimates, constructed using observational rainfall data from an additional 466 pluviometers in the Queensland Flood Warning Network. The new SILO rainfall estimates led to an improved representation of modelled flow for the Tully River in the P2R, Wet Tropics, catchment model.

Modellers should therefore be aware of the potential impacts of pluviometer inception or cessation on rainfall interpolation and the effects on modelled runoff, particularly in regions of low pluviometer areal density.

Further study should be undertaken to investigate the benefits from using spatial rainfall estimates constructed using pluviometer data collected by individuals, groups or organisations in addition to the Bureau of Meteorology, versus the increased uncertainty due to the potentially lower quality standards employed in the collection of such data.

Keywords: *SILO, rainfall, interpolation, modelling, flow*

Peel River System Model: Using palaeo-stochastic climate to evaluate water security options in a catchment with high surface-groundwater interaction

M. Sugiyanto and R. Beecham [a]

[a] *Knowledge Division, Department of Planning, Industry and Environment, Parramatta, 2150, NSW Australia*
Email: Michael.Sugiyanto@dpie.nsw.gov.au

Abstract: The Peel catchment located in New South Wales is known for its high surface water and groundwater interactions especially along its river channel. Its water sources are managed by two groundwater Water Sharing Plans and two surface water Water Sharing Plans. Unlike most of other inland NSW catchments, the Peel is characterised by high usage of its surface water in Chaffey Dam and Dungowan Dam for town water supply in Tamworth, which has a population size of 60,000 people that is projected to increase significantly by 2060. Growing population as well as future climate risk means that Tamworth is exposed to water security risk.

River system models typically focus on surface water balance in a catchment, from rainfall, to runoff generation and how they move from upstream to downstream. A typical component of the river water balance is the transmission loss along the river. This transmission loss has usually represented by an average loss relationship as a function of upstream flow. In this model, we have represented the transmission loss as a flux into the groundwater table along the Peel River which depends on antecedent condition. Within limited data availability, we have constructed groundwater level predictors using prior rainfall and evaporation as climate indicator. During the recent drought in 2018-2020, there has been a significant transmission loss to the groundwater table along its river, especially between Chaffey Dam and Tamworth. Having climate dependent groundwater fluxes as a mechanism for transmission loss means that drier period such as the recent drought will be represented more realistically in the model.

In addition to the governing water sharing rules at catchment scale, this model is also configured with the latest drought management plan for Tamworth that manages the town's overall demand as a response to water availability. The model has also been used to develop the new Dungowan Dam business case as it provides a catchment overview, water security to Tamworth and third-party impacts. Palaeo-stochastic climate data has been used to evaluate different option assessments effectiveness over the long term, beyond the historical climate record. The assessment of such business case also evaluates the effectiveness and impact during dry periods. Therefore, the representation of climate dependant groundwater fluxes as a mechanism for transmission loss builds on the confidence of the model robustness and outcome.

Keywords: *River system modelling, climate risk, water supply security, stochastic climate models, surface-groundwater interaction*

EXTENDED ABSTRACT ONLY

Strategic economic assessment of infrastructure and policy changes within dynamic river systems

N. Taylor[1], B. Carey[1], and K. Roche[1]

[1]Regional Water Strategies, Strategy Division, Water Group, Department of Planning, Industry and Environment NSW, Australia
Email: benjamin.carey@dpie.nsw.gov.au

Abstract: The Department of Planning, Industry and Environment (DPIE) of NSW Government is in the process of developing Regional Water Strategies (RWS) across NSW to enhance the management of water. The strategies aim to determine how much water a region needs to meet future demand, and identify challenges and choices involved in meeting those needs. The strategies will set out actions to manage risks to water security; enable economic prosperity; protect and enhance the environment; recognise and protect Aboriginal water rights, interests and access to water; and identify actions that can achieve these in a cost-effective manner.

Water in NSW is a constrained resource. As options may aim to achieve multiple objectives and compete for the same resources, it is possible that one will meet its main objective but have negative impacts on others. In developing the strategies, a risk-based approach has been applied to assess the viability of the range of options being considered. This requires, among other considerations, interpreting hydrologic datasets and understanding the economic implications for different extractive water users. Additional considerations included, but not discussed within this paper, include environmental outcomes and Aboriginal water rights, interests and access to water. No weighting or ranking of importance is presumed on these considerations.

The model discussed within this paper is a regional water value function that translated the value of water at different levels of availability for each extractive user. This approach enabled the comparison between options aimed at reliability of essential water supply and those that sought to improve regional economic activity, accounting for climate variability. The economic modelling of a wide range of hydrologically simulated outcomes for the region allows for the comparison of infrastructure and policy options under a common framework.

Strategic economic modelling is currently being undertaken on eleven regions within NSW. The modelling, which broadly considers changes in economic outcomes of key extractive water users, is used within a cost-benefit analysis framework to determine the economic efficiency of applying an intervention to the region. Identified key water users include towns, annual agricultural producers, and perennial agricultural producers.

All options considered are being examined over multiple 40-year time frames across three sets of climatic data. Extractive behaviors of key water users in these climates are generated over long time frames using catchment level river system hydrologic models. The climatic datasets include 130-years of daily recorder data, 10,000-years of paleo-stochastic climate data, and 10,000-years of stochastic data with climate projection using NARCliM 1.0. This results in 14 40-year analysis time frames across the known climatic period of the daily recorder data, and 1,000 40-year analysis timeframes across each of the stochastic and NARCliM predictions.

For each of the 40-year analysis periods a base case scenario and a scenario for each intervention is being considered within the hydrologic modelling. The base case scenario considers the catchment with current infrastructure and policy settings. The hydrologic outputs are translated to economic outcomes through the consideration of the marginal benefit of each volume of water extracted, the cost of the intervention, and the timing of outcomes. This approach allows for a robust quantitative examination of the incremental economic benefit (or disbenefit) of proposed interventions, when compared to the corresponding climates' base case scenario, across a wide range of historic and potential future climatic predictions.

The paper presents an overview of the economic modelling methodology, completed using the R programming language, implemented across a typical region and a discussion of key results.

Keywords: *River system modelling, NSW regional water strategy, stochastic climate data, economic modelling, cost-benefit analysis*

A random forest approach to drought prediction in Australia

A.J. Gibson[a] and **G.R. Hancock**[a]

[a] *School of Environmental and Life Sciences, University of Newcastle, Callaghan, 2308, Australia*
Email: abraham.gibson@newcastle.edu.au

Abstract: Improved drought management and preparedness hinges upon reliable forecasts, however prediction of drought onset and termination remains elusive due the protracted nature of drought and its spatial variability. In the Australian context, previous research has linked the occurrence and severity of drought to the state of the major ocean-atmosphere climate drivers. This study builds on this existing knowledge base by using metrics of these climate drivers to hindcast metrological drought onset and termination across Australia from 1900–2015. This was achieved through a random forest approach to model the six-month Standardised Precipitation Index (SPI6) during drought onset and termination at 14 stations across Australia.

We found that drought onset has a distinct seasonality which varies regionally in line with the climate drivers. The timing of drought termination, in contrast, did not have as clear a seasonal pattern and was sensitive to the threshold chosen to define drought termination. Overall, the models explained up to 75% of variation in the SPI6 in the six months prior and post the drought onset and termination month, however model success varied spatially. This study highlights the need for region-specific approaches to drought prediction and reinforces support for developing long-lead forecasting around the state of large-scale ocean-atmosphere climate drivers. Importantly, by characterising regionally specific expressions of drought, we may improve predictability and ultimately our resilience to drought.

Keywords: *Drought prediction, random forest, drought onset, drought termination, meteorological drought*

EXTENDED ABSTRACT ONLY

Regional trends in flood event rainfall-runoff coefficients

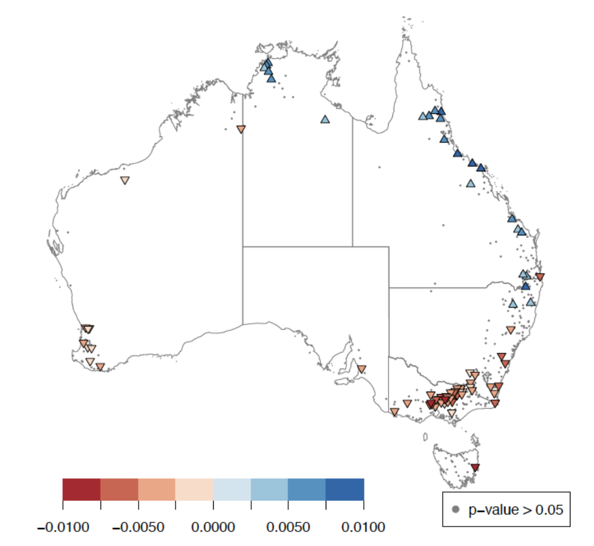
Michelle Ho [a], Conrad Wasko [a], Elisabeth Vogel [b], Rory Nathan [a], and Ashish Sharma [c]

[a] *Department of Infrastructure Engineering, The University of Melbourne, 3010, Australia*
b Hydrological Applications, Hydrology Section, Bureaus of Meteorology
Email: m.ho@unimelb.edu.au

Abstract: The potential for flood-induced disasters motivates a keen interest in how floods may change into the future. The IPCC's stance (given with moderate confidence) that regional floods will increase is informed by recent observations and projections indicating that precipitation events will intensify with rising temperatures. At present, studies of runoff responses to changes in precipitation have largely focused on frequent precipitation events, peak flows within the runoff response or water yields at seasonal and annual scales. Trends in flooding have yielded results contrary to the hypothesis that increased precipitation intensities will lead increased flood magnitudes, as have assessments of streamflow-temperature relationships, which often show declines in extreme quantiles with higher temperatures. These studies, however, have largely been performed without explicitly considering the role of precipitation.

Here, an analysis of flood event runoff coefficients (the ratio of flood volume to rainfall volume) is used to assess the relationship between extreme precipitation and floods. Using high quality daily streamflow data from the network of 467 hydroclimatic reference stations from the Bureau of Meteorology and catchment average rainfall from the Australian Gridded Climate Data set, flood event runoff coefficients are calculated. The event selection was based on annual maximum precipitation, rather than annual maximum streamflow, to yield an unbiased sampling of antecedent catchment conditions, which influence the resulting flood volume. As we are interested in the runoff response, total flows were separated into baseflows and surface flows using a recursive digital filter. We used trend tests to identify changes in the flood event runoff coefficient for runoff responses to extreme rainfalls. These trend tests were linear regression, Sen's slope, and the Mann Kendall test. The trend tests were applied to different data sets, including: the whole HRS data set, a subset assessing the most recent 40 years, and a further subset of events that were dominated by a single (rather than multiple) bursts of rainfall.

Over the instrumental record, clear regional trends were observed in the flood event runoff coefficient (see figure below) and are similar to trends observed in total annual flows. Runoff generated from extreme precipitation has generally decreased over southern mainland Australia and north and north-eastern Tasmania suggesting a drying of the catchments prior to the occurrence of extreme rainfalls. This reduction in runoff for the same amount of precipitation has implications for delivering "freshes" for maintaining ecohydrology health and recharging water storages. In contrast, runoff generated from extreme precipitation has generally increased in northern Australia indicating increased risks of sediment erosion and to flood infrastructure.



Linear regression slope of the flood-event-runoff coefficient for results significant at the 95th percentile (using bootstrap resampling) for gauged data at hydrological reference stations from 1980-2019.

As the ability to replicate these results in a semi-distributed landscape water balance model would allow for further investigation of how runoff characteristics may change under climate change, the flood event runoff coefficients were recalculated using AWRA-L modelled streamflow. It was found that AWRA-L reproduced the regional historical patterns in runoff trends. This verification process provides a basis for assessing changes in flood event-scale runoff responses using AWRA-L results informed by climate change outputs.

Keywords: *Floods, event rainfall-runoff coefficients, trends, model verification*

Linking moisture transport and extreme precipitation in southeast Australia

C. Holgate[a], I. Rudeva[a], G. Boschat[a], A. Pepler[a], R. McKay[a] and P. Hope[a]

[a]*Australian Bureau of Meteorology*
Email: chiara.holgate@bom.gov.au

Abstract: The transport of moisture from the oceans plays a vital role in Australia's precipitation. In southeast Australia in particular, previous studies have shown moisture transport is key to precipitation variability, extreme precipitation and drought-breaking events (e.g. Rakich et al 2008; Warren et al 2021; Holgate et al 2020). A more comprehensive understanding of the physical processes that control moisture transport from the ocean toward southeast Australia – whether to strengthen the supply of moisture for extreme precipitation or reduce the supply during dry periods – is needed.

One potential mechanism enabling strong transport of moisture from the ocean toward southeast Australia is the presence of a high pressure system in the Tasman Sea region. For instance, in March 2021 a slow-moving high pressure system over the Tasman Sea strengthened onshore moisture transport and contributed to severe weather conditions in southeast Australia. Multiple days of heavy rainfall occurred and resulted in the wettest week on record in some parts of the region (Bureau of Meteorology Special Climate Statement 74). This event highlighted the need to better understand the role of Tasman Sea high pressure systems in creating conditions favourable for extreme rainfall in southeast Australia, to assist early warning and impact mitigation efforts.

We use reanalyses and a Lagrangian-based evaporative moisture source tracing algorithm to explore the role of synoptic systems in transporting moisture from the Tasman/Coral Seas toward southeast Australia. Specifically, we investigate the role of Tasman Sea high pressure systems in strengthening onshore moisture transport and the changing likelihood of extreme precipitation when combined with upper-level anomalies over southeast Australia. This presentation will report on the research undertaken so far, including the methodological approach adopted.

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Keywords: *Moisture transport, extreme precipitation, back-trajectory*

What would happen to the local climate if irrigation was turned off in North-western India?

Huazhen Li [a] **, Min-Hui Lo** [b] **, Dongryeol Ryu** [a] **, Murray Peel** [a] **, Yongqiang Zhang** [c]

[a] *Department of Infrastructure Engineering, Faculty of Engineering & Information Technology, The University of Melbourne, Melbourne, Australia*
[b] *Department of Atmospheric Sciences, National Taiwan University, Taipei, Taiwan*
[c] *Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, China*
Email: huazhenl@student.unimelb.edu.au

Abstract: Irrigation can play an important role in changing the local water cycle and resulting hydroclimate. While irrigation may lead to increased evaporative cooling from wetter soil, it can also increase the greenhouse effect through increased atmospheric water vapor. As a result, the net impact of irrigation on near surface temperature remains unclear. Previous studies on these two competing impacts of irrigation on near surface temperature have found conflicting net effects (Kennedy & Hodzic, 2019; Thiery et al., 2017). Furthermore, the impact of turning off irrigation on sub-daily (daytime and night-time) temperature is rarely examined comprehensively. In this study, the Single Column Atmospheric Model (SCAM) in the Community Earth System Model (CESM) is used to investigate what would happen to the local climate if irrigation was turned off in North-western India. From a seasonal perspective, the influence of irrigation on daily temperature is always higher during the warm and dry season (peak irrigation season) in March-June than during the summer monsoon and winter seasons. Overall, the average daily temperature during the peak irrigation season in North-western India decreased by 0.6°C±0.1°C when irrigation is turned off. Our simulations show the daily temperature decrease without irrigation in North-western India is due to the influence of irrigation on night-time temperature being significantly greater than its influence on daytime temperature in this region. In other words, the difference in maximum temperature between model runs with and without irrigation was much less than the difference in minimum temperature. Hence, any increase in daytime temperature due to stopping irrigation is overset by night-time cooling. The decreasing of night-time temperature when local irrigation is turned off is mainly due to the energy dissipation caused by the decrease of water vapor and clouds in the atmosphere. For North-western India, relative humidity and downward longwave radiation are most sensitive to changes in irrigation volume, followed by minimum daily temperature and maximum daily temperature, and 2m air temperature is the least sensitive variable to changes in irrigation volume. Our results underline that the impact of irrigation is a complex interplay of evaporative cooling and greenhouse warming and still needs to be further investigated.

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Keywords: *Climate change, irrigation, night-time temperature, SCAM*

On the robustness of annual daily precipitation maxima estimates over Monsoon Asia

Phuong Loan Nguyen[a], **Margot Bador**[a], **Lisa V. Alexander**[a], **Todd P. Lane**[b] **and Chris C. Funk**[c,d]

[a] *Climate Change Research Centre and ARC Centre of Excellence for Climate Extremes, UNSW Sydney, Sydney, New South Wales, Australia*
[b]*School of Geography, Earth and Atmospheric Sciences and ARC Centre of Excellence for Climate Extremes, The University of Melbourne, Melbourne, Victoria, Australia*
[c]*US Geological Survey, Centre for Earth Resources Observation and Science, Sioux Falls, SD, United States*
[d]*Santa Barbara Climate Hazard Centre, University of California, Santa Barbara, Santa Barbara, CA, United States*
Email: phuongloan.nguyen@student.unsw.edu.au

Abstract: Understanding precipitation extremes over Monsoon Asia is vital for water resource management and hazard mitigation, but there are many gaps and uncertainties in observations in this region. To better understand observational uncertainties, this study uses a high-resolution validation dataset to assess the consistency of the representation of annual daily precipitation maxima (Rx1day) over land in 13 observational datasets from the Frequent Rainfall Observations on Grids (FROGS) database. The FROGS datasets are grouped into three categories: 1. *in situ*-based, 2. satellite-based with correction to rain gauges and 3. satellite-based without correction to rain gauges. We investigate three sub-regions: Japan, India, and the Maritime Continent based on their different station density, orography, and coastal complexity.

We find that there are broad similarities in the spatial and temporal distributions among *in situ*-based products compared to satellite products (with or without station correction) over Monsoon Asia. Satellite products with correction to rain gauges show better general agreement and less inter-product spread than their uncorrected counterparts.

However, this comparison also reveals strong sub-regional differences that can be explained by the quantity and quality of rain gauges. First, focusing on *in situ* datasets only, we find a better agreement over dense data regions like Japan. Conversely, regions with no stations (e.g., Myanmar, Tibetan Plateau) or sparse station networks (e.g., the Maritime Continent) stand out over other regions as having the largest differences in precipitation extremes estimates. Secondly, over the data dense region of Japan, corrected satellite products show similar spatial and temporal patterns between themselves and compared to the *in situ*-based products that are used to correct them. In addition, the inter-product spread among corrected satellite estimates is closer to the spread for *in situ*-based products than for their uncorrected counterparts despite the larger number of satellite products. On the contrary, over poorly sampled regions (e.g., India and the Maritime Continent), both uncorrected and corrected satellite clusters are similar to each other and have much larger spread compared with *in situ*-based products. In addition, we also show that the length of record available at each station can also affect the satellite correction over these poorly sampled regions.

Clearly, the quantity and quality of the station network have implications for the reliability of the *in situ*-based products derived and the satellite products that use a correction to *in situ* data. We show that satellite products can have the spatial imprints of the underlying *in situ* data. Therefore, they cannot be considered as the "perfect solution" to replace the lack of *in situ* data over data-sparse regions of Monsoon Asia.

Given the large observational uncertainties over Monsoon Asia, there is no single best dataset for assessment of Rx1day. In all cases, we recommend users understand how each dataset is produced in order to select the most appropriate product to estimate precipitation extremes to fit their purpose.

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Keywords: *Precipitation extremes, observational uncertainties, in situ, satellite observation, satellite correction*

No 'hook' structures in extreme precipitation-temperature scaling

J.B. Visser [a], **C. Wasko** [b], **A. Sharma** [a] **and R. Nathan** [b]

[a] *School of Civil and Environmental Engineering, University of New South Wales, Sydney, New South Wales, Australia,* [b] *Department of Infrastructure Engineering, University of Melbourne, Melbourne, Victoria, Australia*
Email: j.visser@unsw.edu.au

Abstract: Observational studies of daily and subdaily precipitation-temperature relationships, termed apparent scaling, intend to provide improved insights on potential changes in precipitation extremes due to a warming climate. However, large variations in apparent scaling across temporal and spatial scales have been found across the globe, creating uncertainty around the use of apparent scaling rates as a foundation for projecting future precipitation extremes. Various physical and methodological factors have been found to influence apparent scaling results, including climate, season, and the accumulation period of precipitation. In cooler climatic regions, daily precipitation extremes tend to scale with temperature at rates close to the Clausius-Clapeyron (CC) relation (~7 %/°C). However, in warmer climatic regions, decreasing precipitation totals at higher temperatures induce negative apparent scaling, producing a strong peak-like or 'hook' structure (Figure 1). This second order discontinuity contrasts with long term trend analysis of annual maximum daily precipitation, which indicates positive scaling close to CC, with greater rates in the tropics.

To investigate the temporal and spatial discrepancies in apparent scaling results, we propose an apparent scaling analysis where precipitation-temperature pairs are conditioned on storm duration. Sub-daily precipitation and temperature data for 385 synoptic stations across Australia are analysed. We find negative apparent scaling reported at elevated temperatures is due to a decrease in the precipitation duration, and not a decrease in the precipitation intensity. Although duration conditioning improves the consistency of apparent scaling results, the required duration subsetting greatly reduces the number of precipitation events per analysis. Consequently, we introduce standardized pooling of precipitation-temperature pairs across Köppen-Geiger climate zones.

Pooled apparent scaling results indicate peak 1-hr and average precipitation intensities of precipitation events increase with temperature across all storms durations and climate zones analyzed. For shorter duration storms (< 6 hr), peak 1-hr intensities within precipitation events are found to increase with temperature at rates close to or exceeding CC, with elevated scaling (10 - 14%/°C) found in tropical regions. Comparable scaling rates are found for average precipitation intensities of short duration storms, although slightly reduced compared to peak 1-hr intensities. With increasing duration, both 1-hr peak and average intensity scaling rates decrease but remain positive.

Our results indicate that conditioning on event duration improves the robustness of apparent precipitation-temperature scaling. Apparent scaling rates are found to be consistent with historical trends, pointing to an increase in future precipitation intensities. We advocate for the use of event-based methods using subdaily data when calculating apparent scaling, while discouraging the use of daily precipitation data due to the non-consideration of the duration of precipitation.

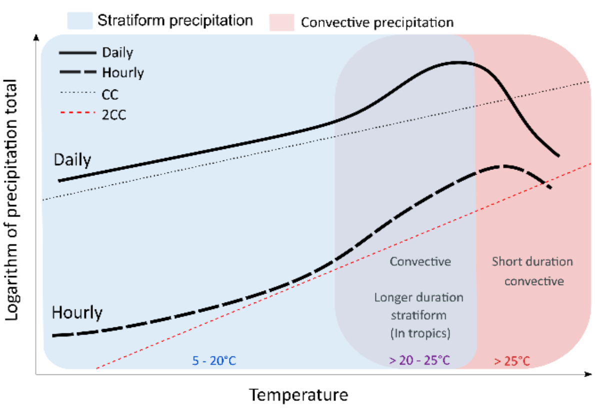

Figure 1. Schematic representation of the influence of precipitation type on apparent scaling of extreme precipitation intensities with temperature. Decreasing precipitation totals due to shorter event durations at higher temperatures create a peak-like or 'hook' structure.

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Keywords: *Extreme precipitation, temperature, scaling, Clausius-Clapeyron*

Changes in antecedent soil moisture under global warming shift flood timing

Conrad Wasko[a], **Rory Nathan**[a] **and Murray C Peel**[a]

[a] *Department of Infrastructure Engineering, University of Melbourne, Parkville, 3010, Australia*
Email: conrad.wasko@unimelb.edu.au

Abstract: Climate change is intensifying rainfalls across the world yet changes to flooding remain mixed. Some parts of the world are experiencing decreases in flooding, while other parts are experiencing increases. Shifts in flood timing are also mixed. Some parts of the world are experiencing shifts to earlier flooding, and others to later flooding. As small changes in flood timing can have severe ecological consequences, as well as changing flood risk and impacting water supplies, it is crucial to understand how Australia's flood timing is changing. Here, we use high-quality streamflow, largely free of snowmelt, from 221 catchments across Australia to investigate the influence of shifts in soil moisture and rainfall maxima on annual streamflow maxima timing.

In tropical regions and across Australia's eastern seaboard, annual maxima rainfall has a strong late summer seasonality, with maxima generally occurring in January-February. In the south-west of Australia, annual maxima rainfalls exhibit a strong winter seasonality. Interestingly, in the south-east, annual maxima rainfall show no strong seasonality suggesting that extreme rainfall events can occur at any time of the year with equal probability. Soil moisture maxima also exhibit a strong seasonality across Australia's north and eastern seaboard generally occurring in February-March. In the south-west, soil moisture peaks around July-August, and in the south-east August-October, with the strength of this seasonality stronger than that of rainfall maxima. Annual flood maxima seasonality closely resembles that of the soil moisture maxima, with a late summer peak in the tropics and eastern seaboard and peaking in the late winter-early spring peak in the south. This suggests, in tropical areas, flood timing is strongly linked to the timing of both rainfall and soil moisture annual maxima. However, in southern Australia, flood timing is more correlated with soil moisture maxima than rainfall maxima.

The correlation between flood, soil moisture, and rainfall timing is dependent on the event severity: For less extreme events flood timing is more correlated to soil moisture timing, whereas rainfall timing becomes more and more correlated to flood timing as the rainfall severity increases. For the first time, we use circular regression as a method of investigating non-stationarity in flood timing. We find that flood timing is shifting to earlier in the year in the tropics and later in the year in the southwest of the continent. The shifts to earlier flood timing are consistent with increases in mean rainfalls and soils becoming saturated earlier in the wet season, while in the south-west declining mean rainfalls and drying soils mean that it is taking longer for the soils to saturate before flooding occurs. In southeast Australia, there is evidence that the mechanisms controlling flood seasonality are changing with a reversal of trends post Millennium Drought. Overall, we conclude changes in soil moisture timing, compared to changes in rainfall timing, have a greater influence on changes in annual maxima streamflow flood timing.

Keywords: *Flooding, flood timing, climate change, extreme rainfall, soil moisture*

National Hydrological projections for Australia: understanding risks to future water availability

Ulrike Bende-Michl[a], Louise Wilson[b], Elisabeth Vogel[a], Justin Peter[a], Wendy Sharples[a], Pandora Hope[a], Vjekoslav Matic[a], Sri Srikanthan[a], Margot Turner[a], Alison Oke[a], Zaved Khan[a], Jake Roussis[a], Vi Co Duong[a], Andrew Frost[a] and Elisabetta Carrara[a]

[a] *Bureau of Meteorology, Australia*
[b] *UK Meteorological Office, UK*
Email: Ulrike.Bende-Michl@bom.gov.au

Abstract: Australia is one of the world's driest continents, its water-sensitive industries and eco-systems depend on the availability of already scarce surface and groundwater resources, such that there is an emerging need to develop mitigation strategies to adjust for a drier future. Thus, understanding changes in water availability due to climate change and associated impacts is a priority for Australia.

To understand those risks and to mitigate negative impacts of a changing climate, Australia's water policy, management and infrastructure decision making needs detailed high-resolution climate and water forecast and projections. In Australia, currently, hydrologic change information exists in fragmented form; ranging from multiple state based or regional downscaling efforts, across limited timescales and which use different interpretation methods for hydrologic impact assessment – preventing a nationally consistent impact assessment across multiple spatial and temporal scales.

The Bureau of Meteorology is soon to release a seamless national landscape water service called the Australian Water Outlook (AWO), combining historical data on water availability with forecast products, as well as hydrological impact projections, using the Bureau's Australian Water Landscape Water Balance model (AWRA-L) (Frost and Wright 2018). Additionally, consistent downscaling and bias-correction approaches using three statistical methods as well as a regional downscaling are integrated for the hydrologic projections in the operational framework to produce national consistent future change dataset for climate inputs (rainfall, solar radiation, temperature and wind) and hydrological outputs (soil moisture, evapotranspiration and runoff).

Projection results feature many sources of uncertainty, including how future greenhouse gas emissions will develop, how a warmer climate will lead to changes to hydroclimatic features and feedback loops, and the models used to simulate those changes. Acknowledging these uncertainties, the Bureau's National Hydrological Projections ensembles provide a unique opportunity to examine impacts of plausible future changes on Australia's hydroclimate and its water resources.

This presentation will share an overview of the National Hydrological Projections: the methodology used to generate national consistent hydrological projections dataset, a user interface to rapidly explore plausible futures in water availability changes, eight regional discrete future hydroclimate assessment reports as well as a novel storyline approach (Sheperd et al., 2018), which clearly communicates risks and impacts to Australia's future water availability from plausible projections scenarios.

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Keywords: *Climate change, water resource availability, national hydrological projections dataset*

Decreases in relative humidity with climate change

Eleanor Denson[a], Conrad Wasko[a] and Murray Peel[a]

[a] *Department of Infrastructure Engineering, University of Melbourne, Parkville, 3010, Australia*
Email: conrad.wasko@unimelb.edu.au

Abstract: Increases in temperature due to climate change are projected to have severe consequences on our environment. On the one hand higher temperatures will increase extreme rainfalls due to increases in the moisture holding capacity of the atmosphere. On the other, higher temperature are likely to increase potential evaporation leading to greater water stress. However, both changes in rainfall, and changes to actual evaporation are modulated by the amount of moisture in the atmosphere, as measured by humidity. Extreme rainfalls can only increase if there is enough moisture available to sustain the increased rainfall, and evapotranspiration is modulated by evaporative demand which has an inverse relationship to the amount of moisture in the atmosphere.

There are two competing theories for how relative humidity will change with climate change. The first suggests relative humidity will remain constant as increasing temperatures increase both evaporation and moisture storage in the atmosphere, with the two-changing relative to each other to keep relative humidity quasi-constant. However, another theory is that as land areas are warming at a greater rate than the ocean, and, as most moisture is sourced from the ocean, saturated air parcels from the ocean will become subsaturated over land resulting in decreased relative humidity.

Observational evidence of changes in relative humidity are conflicting with few parts of the world exhibiting statistically significant trends. The majority of studies use coarsely gridded reanalysis products, and while there is evidence from some observational studies that relative humidity over land is being conserved other studies find evidence against constant relative humidity over land. Here we use station data to investigate trends in relative humidity to answer the question, how has relative humidity over land change historically? We present one of the longest trend studies ever published investigating trends in relative humidity across Australia over 1955–2020.

We find that absolute humidity, measured by dew point temperature, has remained relatively constant, while temperatures have increased, and consequently relative humidity has decreased. Performing field significance tests, we find these negative trends in relative humidity cannot be explained by chance. The magnitude of the relative humidity trend is directly linked to the strength of the temperature change, with regions that experience greater temperature increases experiencing greater decreases in relative humidity. Sensitivity testing found that the El Niño–Southern Oscillation and changes in the number of rain days across Australia have a negligible impact on the change in relative humidity, allowing us to conclude that changes in relative humidity are temperature driven. On average, across Australia, relative humidity is decreasing by approximately −1%/decade. As the dew point temperature is not changing, our results suggest this decrease in relative humidity is not due to a lack of water available for evaporation, but is instead because evaporation is not increasing in line with temperature increases.

Keywords: *Humidity, relative humidity, dew point temperature, extreme rainfall, trend*

EXTENDED ABSTRACT ONLY

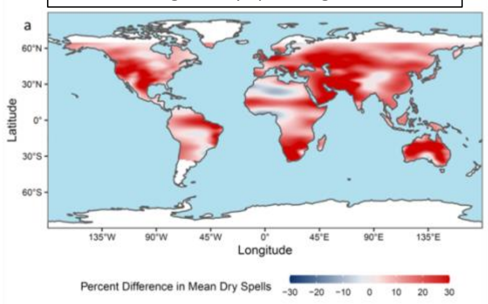
When there is less water when you need it most

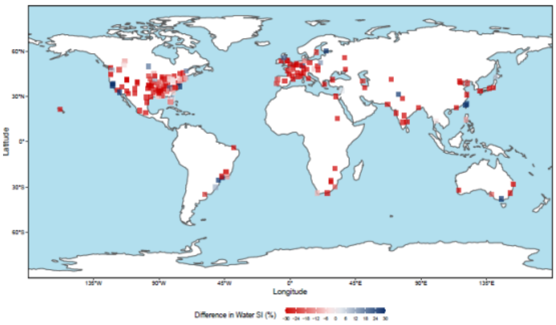
Suresh Hettiarachchi[1], **Conrad Wasko**[2], **and Ashish Sharma**[1]

[1] School of Civil and Environmental Engineering, The University of New South Wales, Sydney, New South Wales, Australia, 2052
[2] Department of Infrastructure Engineering, University of Melbourne, Parkville, Victoria, Australia, 3010
Email: s.hettiarachchi@unsw.edu.au

Abstract: Air to breath and water to drink are life critical factors that affect all living creatures on Earth. As such, water scarcity due to short term lack of rain casts dire consequences to human life and safety just as much as risks associated with intensified storm extremes. Increasingly frequent water crises and forest fires around the world, such as those that occurred in Australia and California between 2017-2019, highlight the catastrophic consequences of longer periods without rain. The threat of extreme storms associated with a changing climate is well documented in literature. Similarly, there is extensive research on water supply concerns with climate change. However, the majority of current research focuses on the impacts of multi-year drought and uses monthly or annual average rainfall to investigate impacts to water supply. Here we look at intra-seasonal changes in rainfall patterns and evaluate if these changes can have an impact on water supply.

Global change in dry spell length in





Impact of longer dry spells on global water stress

To do so, we analyse over 100 years of rainfall and related temperature data at approximately 30,000 gage sites around the world. We compare rainfall patterns and water availability between warmer and colder summer seasons as an indicator of changes that can be expected due to higher temperatures. The base assumption is, since the climate is projected to get warmer, it is more likely that seasonal rainfall patterns will be more like the warmer summers from the past. The first figure shows that there is an overwhelming increase in the length of intra-seasonal dry spells, or continuous days without any rain in warmer summers. The sharpest changes tend to match areas that are already showing increases in water stress and forest fires, highlighting the threat of longer dry spells to life on earth. To look at the impact of these longer summer dry spells on water supply, we estimate streamflow based on the antecedent precipitation index and use population as an index of water demand for 200 of the largest cities around the world. As shown in the second figure, we show that water stress can increase as much as 30% as a consequence of the longer seasonal dry spells. This suggests that changes in seasonal dry spells also can have significant impacts on water supply and should be considered within planning and policy making, especially in some of the larger cities around the world.

Keywords: *Warming climate, longer dry spells, higher water stress*

Investigating climate variabilities in Pan Third Pole based on CMIP6 predictions through Bayesian Model Averaging

Z. Liu [a], Q.Y. Duan [a], X.W. Fan [b] and C.Y. Miao [b]

[a] *College of Hydrology and Water Resources, Hohai University, Nanjing, China*
[a] *Faculty of Geographical Science, Beijing Normal University, Beijing, China*
Email: zhuliu@hhu.edu.au

Abstract: Pan Third Pole (PTP) region includes Tibet Plateau (TP), part of Central Asia (CA) and Southeast Asia (SEA) and it is one of the places on earth that are most sensitive to climate change. Meanwhile, PTP origins a series of large rivers such as Yangtze River, Yellow River and Lancang-Mekong River, which feed millions of people downstream. Therefore, climate change in PTP has significant impact on livings of local people and water supply. In this study, 16 model predictions from the Coupled Model Inter-comparison Project Phase 6 (CMIP6) and Climate Research Unit (CRU) observations are used to evaluate historical precipitation and temperature changes from 1901 to 2010 for TP, CA and SEA respectively. In addition, Bayesian Model Averaging (BMA) approach is applied to obtain the weighted multi-model mean prediction and the BMA values are further used to assess the climate variabilities in the future under 4 SSP-RCP scenarios for the PTP region. Results indicate that temperature is significantly underestimated by CMIP6 models in TP whereas precipitation is overestimated for CA and TP. Taylor diagram shows that most CMIP6 models do not predict precipitation very well in SEA. In addition, both annual mean temperature and annual total precipitation have an increasing trend for the past century till the end of this century and increasing amount becomes more as severer SSP-RCP scenario is used.

Keywords: *Climate variability, CMIP6, Pan Third Pole, Bayesian Model Averaging*

More intense daily precipitation in CORDEX-SEA regional climate models than their forcing global climate models over Southeast Asia

Phuong Loan Nguyen[a], **Margot Bador**[a], **Lisa V. Alexander**[a], **Todd P. Lane**[b] **and Thanh Ngo-Duc**[c]

[a] *Climate Change Research Centre and ARC Centre of Excellence for Climate Extremes, UNSW Sydney, Sydney, New South Wales, Australia*
[b]*School of Geography, Earth and Atmospheric Sciences and ARC Centre of Excellence for Climate Extremes, The University of Melbourne, Melbourne, Victoria, Australia*
[c]*Department of Space and Applications, University of Science and Technology of Hanoi, Vietnam Academy of Science and Technology, Vietnam*
Email: phuongloan.nguyen@student.unsw.edu.au

Abstract: The ability of Regional Climate Models (RCMs) to accurately simulate the current climate is increasingly important for impact assessments over Southeast Asia, identified as one of the world's most vulnerable regions to climate change.

In this study, we evaluate the performance of a set of regional high-resolution simulations from the Coordinated Regional Climate Downscaling Experiment-Southeast Asia (CORDEX-SEA) in simulating rainfall over the region. Simulations of the 1982–2005 seasonal mean climatology of daily precipitation and precipitation distribution over land are compared to observations from different sources (i.e., *in situ*-based and satellite-based) in an effort to consider observational uncertainties. We also evaluate to what extent the precipitation distribution in RCMs is closer to observations than their associated forcing Global Climate Models (GCMs).

Observational estimates of seasonal daily mean precipitation over Southeast Asia have large uncertainties, especially over the Maritime Continent, which makes the evaluation of models complicated. Despite these difficulties, our results highlight that RCMs can reproduce some complexities in the spatial distribution of seasonal rainfall but generally have a larger wet bias than GCMs compared to observations. This is particularly the case for the extremes as RCMs generally show a large overestimation of rainfall intensity.

RCMs are usually expected to better represent the daily precipitation distribution (i.e., closer to observed estimates) compared to their forcing GCMs as they are better at resolving sub-grid scales and the key processes for precipitation formation. However, we find that this is often not the case for the CORDEX-SEA simulations evaluated here. On the whole, the RCMs have a rainfall distribution that is further from observations than the distribution from their driving GCMs. Hence, we cannot find a systematic improvement in the representation of simulated precipitation in RCMs, although there are some parts of the precipitation distribution, seasons and grid points for which RCMs are closer to observations than GCMs. Setting aside observations, RCM simulations are 'wetter' than the GCM simulations over the region. Further analyses highlight that this wetter state in RCMs is not primarily driven by the forcing GCM's bias or spatial resolution but is essentially due to the modeling setup of RCMs.

We investigate why simulated daily precipitation is more intense in RCMs over CORDEX-SEA compared to their associated forcing GCMs and find two main explanations. First, an increased supply of moisture from both local and large-scale sources is found in the RCMs, and the reason behind this remains to be understood. Second, we find a general increase in convective precipitation across the region in RCMs. Our findings suggest that a model's ability to simulate precipitation over the region relies more on the RCM setup itself (i.e., parameterization scheme) rather than its forcing GCM. This should be considered when assessing the reliability of RCM precipitation simulations for future projections.

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Keywords: *CORDEX-SEA, Regional Climate Models, precipitation biases, convective parameterizations*

EXTENDED ABSTRACT ONLY

Future rainfall distributions over Victoria, Australia under a changing climate

Surendra P. Rauniyar[a] and **Scott B. Power**[b]

[a] *Australian Bureau of Meteorology, Melbourne, Australia*
[b] *Centre for Applied Climate Sciences, University of Southern Queensland, Queensland, Australia*
Email: surendra.rauniyar@bom.gov.au

Abstract: Many regions of Victoria, the 2nd most populous state of Australia, receive a major proportion of their total annual rainfall during the cool season (April – October). The rainfall during the cool season is very important for agriculture and replenishing reservoirs as evaporation is lower during this season. Victoria has experienced a decline in annual rainfall since the 1960s despite the occurrence of several wet years since then. The decline is found to be driven by a downward trend in cool season rainfall. In fact, the cool season rainfall since the beginning of the Millennium Drought in 1997 is ~12% below the 1900 – 1959 period average. These persistent dry conditions challenge the underlying assumption of stationary climate over Victoria, which is used in defining the historical (baseline) climate for future planning and management of water resources. The recent declines also raise an important question, i.e., which historical period, if any, can be used to estimate future rainfall distributions over Victoria? Furthermore, it is found that the recent drying would not have been as large without the exacerbating influence of the increasing level of greenhouse gases (GHGs) in the atmosphere. If this is the case then one might assume that the drying will continue in future and the raw observations alone may not be sufficient to approximate the future rainfall distributions in the face of ongoing climate change.

In this study, we use the observations and simulated rainfall from 40 CMIP5 climate models under preindustrial, historical, and a high emission scenario (RCP8.5) to provide better estimates of Victorian rainfall distributions for three different future periods of the 21st century: near-term (2010 – 2039), medium-term (2040 – 2069), and long-term (2070 – 2099). We devise a new method by removing the influence of external forcing on Victoria's cool-season rainfall, effectively revealing the variability that might be seen in a stationary climate. Model derived scaling factors (SFs) based on early 20th century are then applied on the adjusted observations to estimate future rainfall distributions. SFs are defined as the ratio of the average rainfall of each decile bin from a future period of interest and the corresponding decile bin average of the selected historical period. We have most confidence in the rainfall estimates based on this approach because our analysis show that picking a shorter period for applying SFs could lead to a misrepresentation of expected climate as there exists a higher chance that the shorter period could have been influenced heavily by internal variability that markedly reduced or increased rainfall averaged over the historical reference period. The results from the new approach are compared with a range of different approaches as well, as used in other previous studies.

We find large model-to-model differences in the estimation of future rainfall distributions under the high emission scenario, which reflects large model-to-model differences in the response of Victorian rainfall to external forcing and the presence of different realisations of internal variability in each model run. Nevertheless, the vast majority of models exhibit drying and the median values of the future rainfall distributions for Victoria decrease monotonically over the remainder of the 21st century. However, there is a 90% chance that in any given year from 2025 onwards the rainfall will be in the range that has been experienced historically indicating that there is a 10% probability that All-Victoria rainfall in any given year could go beyond historical experience. The models suggest that the probability of being below the observed 5th percentile in any given year will increase in the future and will become three times larger by the end of the century (i.e. occurring in about 15% of years under a high emission scenario). We also find that none of the historical periods provide an accurate approximation of expected future distributions of Victorian rainfall. The rainfall distributions based on the historical period 1900 – 2018, for example, tends to overestimate rainfall compared with projected distributions while the distribution based on the recent dry period (1997 – 2018) is too narrow and consequently underestimates the range of possibilities projected as it omits the important aspects of climate variability observed previously. However, our confidence in the results based on the new methodology is still low because of model deficiencies in simulating the observed rainfall changes and variability over Victoria.

Keywords: *External forcing, internal variability, scaling factors, future rainfall distributions, CMIP5*

How does salty snowfall in Antarctica help us understand Australian hydroclimate risk?

Danielle G. Udy[a,b,c], Tessa R. Vance[c], Anthony S. Kiem[d] and Neil J. Holbrook[a,b]

[a] Institute for Marine & Antarctic Studies, University of Tasmania, Hobart, Tasmania 7004, Australia
[b] ARC Centre of Excellence for Climate Extremes, University of Tasmania, Hobart, Tasmania, 7004, Australia
[c] Australian Antarctic Program Partnership, Institute for Marine & Antarctic Studies, University of Tasmania, Hobart, Tasmania 7004, Australia

[d] Centre for Water, Climate and Land, College of Engineering, Science and Environment, University of Newcastle, Callaghan, NSW 2308, Australia

Abstract: Droughts and floods have devastating impacts on water security, agriculture, and human health, but short instrumental records (~100 years) make it difficult to accurately quantify past, present and future hydroclimate risk, limiting the development of appropriate water policies and infrastructure. Palaeoclimate records provide an opportunity to contextualise recent drought and flood history against the last millennia, but high resolution (seasonal – annual) rainfall proxies are spatially limited across Australia (Kiem et al. 2020; Flack et al. 2020). The sea salt aerosol concentration in the Law Dome ice core (East Antarctica) provides a complementary remote rainfall proxy for eastern Australia, with increased (decreased) sea salt concentrations in the ice core correlated to wet (dry) periods over key agricultural and water supply catchments (Vance et al. 2013; 2015). Interestingly, the spring-summer seasonal connection between the Law Dome ice core and subtropical eastern Australian rainfall variability is stronger than the influence of the three main modes of climate variability known to influence Australia's rainfall (El Niño-Southern Oscillation, Southern Annular Mode, and Indian Ocean Dipole). However, the physical mechanisms underpinning the observed teleconnection were unknown until now. Here we demonstrate, through synoptic typing (using Self Organising maps; Udy et al. 2021), that the ice core record provides a proxy record of the synoptic circulation connecting Southern Ocean wind conditions to rainfall processes across eastern Australia. This dynamic understanding enhances the practical usefulness of millennial-scale rainfall reconstructions from the ice core record, as well as identifying dynamic processes that need to be realistically represented in climate models for future rainfall prediction over eastern Australia.

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Keywords: *Hydroclimate, rainfall, synoptic typing*

EXTENDED ABSTRACT ONLY

Comparison and interpretation of future streamflow projections from different climate projection products and hydrological impact modelling approaches

Hongxing Zheng[a], Francis HS Chiew[a], Stephen P Charles[a], Nick J Potter[a], David E Robertson[a], David A Post[a], Joel Bailey[b], Geoffrey Steendam[c], Rebecca A Lett[c], Marcus Thatcher[a], Fei Ji[d] and Jozef Syktus[e]

[a]*CSIRO Land and Water (Canberra, Perth, Melbourne)*
[b]*Murray-Darling Basin Authority*
[c]*Victorian Department of Environment, Land, Water and Planning*
[d]New *South Wales Department of Planning, Industry and Environment*
[e]*School of Biological Science, University of Queensland*
Email: francis.chiew@csiro.au

Abstract: Projections of climate change impact on future water resources and streamflow characteristics are generally developed by comparing hydrological model simulations for a future time period relative to a historical time period. The climate change signal is usually obtained from global climate models (GCMs) or dynamic downscaling models (or regional climate models, RCMs). There are a large number of global climate model outputs from different modelling groups across the world, and they provide some indication of the uncertainty or range in the future climate projections. Dynamic downscaling provides much higher spatial resolution outputs and potentially has realised added value, particularly in high elevation and coastal regions. However, because of the long computer run times, there are only limited outputs from dynamic downscaling, supported by the different states in Australia to inform regional assessments and adaptation.

Different approaches have been used to generate the future climate inputs for hydrological modelling. They generally fall into three categories. The first is the empirical scaling approach, where the historical daily rainfall series is scaled by the change signal in the GCM or RCM (at the annual, seasonal or daily level) to obtain the future rainfall series. The second is the bias correction approach, where a relationship is developed between the historical RCM daily rainfall and the observed rainfall, and this relationship is then used to translate the future RCM rainfall to catchment rainfall. The third approach is to generate stochastic future rainfall series that reflects the change signals in the various rainfall characteristics. Each approach has advantages and limitations.

This paper presents a comparison of future streamflow projections for catchments in the Murray-Darling Basin from hydrological modelling informed by different climate projection products and approaches used to generate future rainfall series. The results indicate that, as expected (because of more intense high extreme future rainfall), empirical daily scaling leads to higher future streamflow compared to the empirical seasonal scaling, but only slightly, and more so for high flow events than for average streamflow volume. Streamflow projections from modelling using bias corrected rainfall can be different from modelling using empirically scaled rainfall, but there is no consistent indication of higher or lower streamflow estimates within and across the different RCMs. The range in future streamflow projections is large, both within and between the GCMs and different state RCM products. The RCM projections can also be quite different from the host GCMs providing the RCM boundary conditions.

The multitude of projections products and impact modelling approaches can be confusing and adds to the challenge of impact assessment and adaptation. The understanding, interpretation and communication of these projections are therefore important, and needs to be fit for purpose for the application. Nevertheless, the choice often does not matter for the broad applications or objectives. For example, practically all the projections point to a drier future in the southern Murray-Darling Basin, which water resources planning need to adapt to.

Acknowledgements: This research is supported by CSIRO, Murray-Darling Basin Authority and Victorian Water and Climate Initiative (VicWaCI). The dynamic downscaling outputs are obtained from projects supported by the Victorian Department of Environment, Land, Water and Planning, New South Wales Department of Planning, Industry and Environment, and Queensland Department of Environment and Science.

Keywords: *Climate change, future streamflow projections, global climate model, dynamic downscaling, empirical scaling*

Impact of climate change on key elements of water cycle in the Tianshan Mountains, Central Asia

Yaning Chen [a], **Gonghuan Fang** [a] **and Zhi Li** [a]

[a] *State Key Laboratory of Desert and Oasis Ecology, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, China*

Email: chenyn@ms.xjb.ac.cn

Abstract: Global warming accelerates the water cycle, which has benefits for water availability. The Tianshan Mountains, with its status as "water tower of Central Asia", is situated in the Eurasia hinterland, far from any ocean. It is the main water source and ecological barrier in Central Asia. The Tianshan Mountains feed the majority of the area's rivers through a combination of ice-snow meltwater in the high mountains, precipitation in the mid-altitude mountains, and fissure water in the low mountains. The hydrological elements and water supplies in the Tianshan Mountains are strongly related to changes in temperature and precipitation, as well as changes in the snow and ice distributed across the mountains. Increases in temperature have important consequences for the hydrological cycle, particularly in areas dominated by glacier and snow melt.

This study investigated precipitation and temperature changes and their impacts on glaciers, snow cover and hydrological processes in the Tianshan Mountains using station observations, remote sensing data and reanalysis data. The rapid warming affected precipitation amounts and fraction as well as the original glacier/snowmelt water processes, thereby affecting the runoff and water storage. The ratio of snowfall to precipitation (S/P) experienced a downward trend, along with a shift from snow to rain. Spatially, the snow cover area in Middle Tianshan Mountains decreased significantly, while that in West Tianshan Mountains increased slightly. Approximately 97.52% of glaciers in the Tianshan Mountains showed a retreating trend, which was especially obvious in the North and East Tianshan Mountains. River runoff responds in a complex way to changes in climate and cryosphere. It appears that catchments with a higher fraction of glacierized area showed mainly increasing runoff trends, while river basins with less or no glacierization exhibited large variations in the observed runoff changes. The total water storage in the Tianshan Mountains also experienced a significant decreasing trend in Middle and East Tianshan Mountains, but a slight decreasing trend in West Tianshan Mountains, totally at an average rate of −3.72 mm/a. In future, water storage levels are expected to show deficits for the next half-century.

This study sheds light on current and future changes on the elements of water cycle under climate change in the Tianshan Mountains. More efforts should be made on the impacts and mechanisms of these changes on runoff, which is a key factor that controls the available freshwater resources for domestic and agricultural needs.

Keywords: *Water cycle, climate change, water storage, glaciers and snow, Tianshan, Central Asia*

EXTENDED ABSTRACT ONLY

Improving PML-V2 evapotranspiration estimates across China

Shaoyang He [a,b] **and** <u>**Yongqiang Zhang**</u> [a]

[a] *Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, CAS, Beijing, China;* [b] *University of Chinese Academy of Sciences, Beijing, China*

Email: zhangyq@igsnrr.ac.cn

Abstract: Terrestrial evapotranspiration (ET) is an important component of energy balance and water balance. PML-V2 model uses a water-carbon coupled canopy conductance model together with the Penman-Monteith (PM) equation to estimate evaporation from the soil, transpiration from the plant canopy, and evaporation of precipitation intercepted by the vegetation, and gross primary productivity (GPP) (Zhang et al., 2019). Though PML-V2 has been widely used to estimate ET and GPP at 500 m resolution across the globe, it can be potentially improved at local and regional scales.

The objectives of this study are threefold. First, this study improves PML-V2 performance in China by improving its parameterization using observations obtained at 36 eddy covariance flux sites across 9 plant functional types (PFTs). Model validations obtain excellent results for most PFTs, indicated by Nash-Sutcliffe Efficiency (NSE) of 8-day ET varying from 0.60 to 0.90 and Root Mean Square Error (RMSE) of ET ranging from 0.42 to 1.07 mm d^{-1}. The locally parameterized PML-V2 is noticeably better (0.04-1.39 larger for NSE, 0.04-1.34 mm d^{-1} smaller for RMSE) than the global version of PML-V2, and other main-stream ET products (such as MOD16), demonstrating the benefit of using local forcings and local parametrization. Second, we re-run PML-V2 to obtain the updated product of 500m and 8-day resolution of ET and GPP in 2003-2018 across China by using the new parameterization, 500 m resolution of MODIS vegetation inputs, 1-km resolution daily near-surface meteorological forcing and the 30m land use/land cover data. Third, using the new product, we investigate spatial pattern of mean annual ET and ET trends in 2003-2018 across China. Our results indicate that mean annual ET decreases from the southeast to the northwest, with the maximum value above 1200 mm in the southeast and the minimum value less than 100 mm in the northwest (Fig.1a). The ET trend result shows that the areas with ET increased were mainly located in the Yellow River Basin, Huai River Basin and the western Tibetan Plateau (p<0.05) (Fig.1b). On the contrary, the areas with ET decreased are mainly located in Yangtze River Basin, Pearl River Basin and Southeastern River Basin (p<0.05). Our results suggest that there exists a large room to make global evapotranspiration product more locally applicable.

Figure 1a. Spatial pattern of mean annual ET (mm)

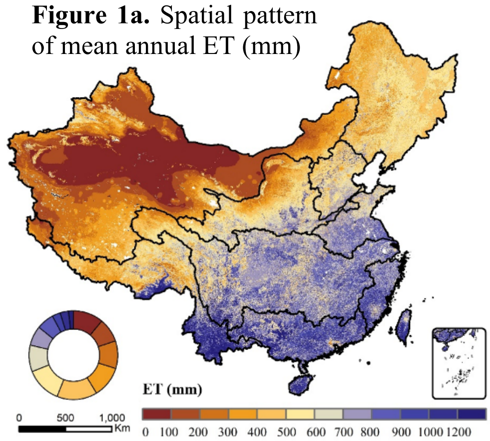
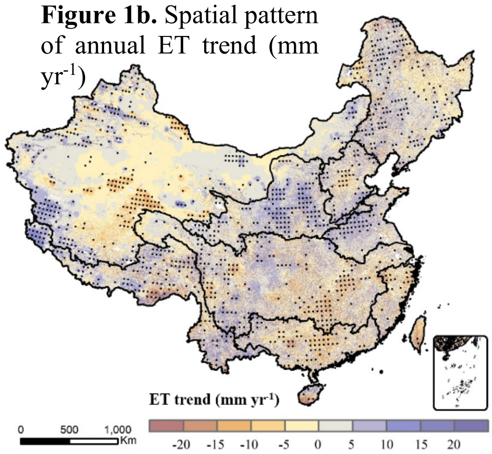


Figure 1b. Spatial pattern of annual ET trend (mm yr^{-1})



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Keywords: *PML-V2, evapotranspiration, parameterization, Eddy covariance, China, trends*

An integrated assessment of surface water dynamics in the Irtysh River Basin during 1990–2019 and exploratory factor analyses

Wenjing Huang[a, b], **Weili Duan**[a, b, *] **and Yaning Chen**[a]

[a] *State Key Laboratory of Desert & Oasis Ecology, Xinjiang Institute of Ecology & Geography, Chinese Academy of Sciences, Urumqi, 830010, China*
[b] *University of Chinese Academy of Sciences, Beijing 100049, China*
Email: sunsade@163.com

Abstract: Climate change and urbanization are jointly impacting on the open surface water area of the Irtysh River in the Arctic Circle. This will affect the economic development and ecology of the countries in the Irtysh River basin and the hydrological cycle of the Arctic Circle. However, the long-term changes of open surface water bodies in the Irtysh River Basin have not been well quantified. To address this, 89,000 Landsat 4,5,7 and 8 images from 1990 to 2019 were used to extract the surface water body area of the Irtysh River Basin and integrated the assessment of open surface water area dynamics. The geographical detector model was used to quantify the factors that affect the area of open surface water bodies. The results show that the total open surface water area of the Irtysh River Basin is an increasing trend over the past 30 years, with a total increase of 88,790 km^2, of which the permanent water body area decreased by 20,800 km^2 and the seasonal water body area increased by 109,590 km^2. In addition, the factors that contributed the most to the dynamics of the surface water area in the Irtysh River Basin were evapotranspiration, precipitation and snow water equivalent, whose contribution rates could reach 72%, 66% and 61%, respectively, with important interactions between factors. This suggests that monitoring dynamics in surface water area requires comprehensive consideration of all factors. Results obtained from this study offer the latest information for fully understanding the spatio-temporal variation of surface water body area and its driving factors in this basin, which could be used to effectively manage water resources for possibly reducing international water disputes and protecting the fragile ecology in the Arctic.

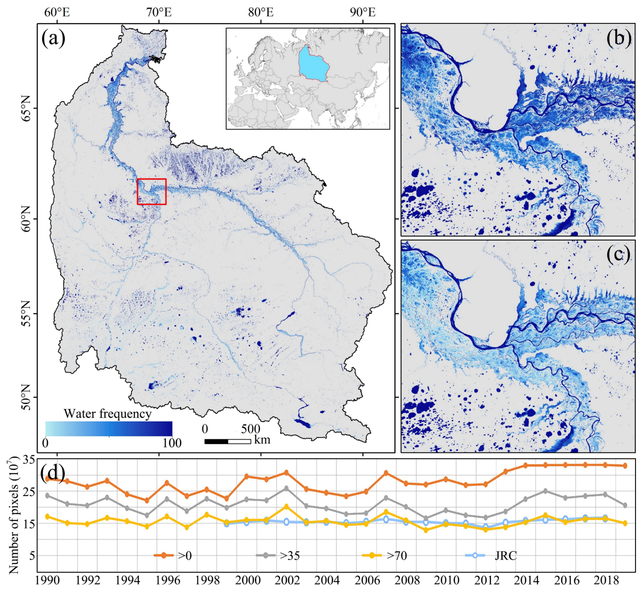

Figure 1. Water frequency maps and water areas using different frequency thresholds. (a) The annual mean water frequency map for the past 30 years. (b) The annual water frequency map in 1990 and its zoom in view of Khanty-Mansiysk. (c) The annual water frequency map in 2019 and its zoom in view of Khanty-Mansiysk. (d) Water areas during 1999–2019 with different FW. The permanent water areas from the JRC data set during 1990–2019 are also shown.

Keywords: *Surface water body area dynamics, Irtysh River Basin, Google Earth Engine, Times series Landsat image, Driving force*

Spatial and temporal variations in land evapotranspiration across Tibetan Plateau during 1982–2016: Results from PML_V2

Ning Ma [a] **and Yongqiang Zhang** [a]

Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, 100101, China
Email: ningma@igsnrr.ac.cn

Abstract: The land evapotranspiration (ET) from Tibetan Plateau (TP) plays a key role in impacting not only the Indian monsoon process but also the water storage change in the Asian Water Tower. However, the amount, changes, and drivers of ET remain poorly understood in such a data-scarce region. This is mainly because the harsh climate impedes intensive ground measurements for understanding ET. In this context, the present study uses a state-of-the-art coupled diagnostic biophysical model, PML_V2, to investigate the spatial and temporal variations in ET across the TP during 1982–2016. The model parameters were calibrated against the observations from 14 eddy-covariance flux towers for six major plant functional types (PFTs, desert, steppe, sparse meadow, dense meadow, forest, and wetland) within TP. The NSE values during the calibration are in excess of 0.88 for five out of six PFTs. The statistical metrics degraded very slightly during the cross-validations, suggesting the PML_V2 is robust in ET estimation in TP.

Based on the PML_V2, we showed that the 35-year mean TP-averaged annual ET rate is 353±24 mm yr^{-1}. ET decreases from the southeastern to the northwestern in TP, which overall follows the spatial patter of the precipitation. The multiyear mean soil evaporation is the main component (64%) of ET, followed by plant transpiration (31%) and canopy evaporation (5%). From 1982 to 2016, annual ET increased significantly with a rate of 1.87 mm yr^{-1} ($p < 0.01$). Sensitivity analysis suggests that the increase in TP-averaged ET over last 35 years was due primarily to increase in precipitation, which contributes to 57%. The air temperature is the second important driver with a contribution of ~20%, while other factors contributions are all less than 10%.

Across the TP, the dominated factor of ET's interannual variation is precipitation over most parts of it except certain regions in the southeastern and eastern TP, where net radiation and temperature become the primary drivers, respectively (Figure 1). Spatially, with rise in aridity index, the number of grids over which ET was mainly controlled by precipitation reduces, while that dominated by temperature and net radiation increases. The results of this study are of great importance for facilitating our understanding of hydrological processes over high-elevation regions.

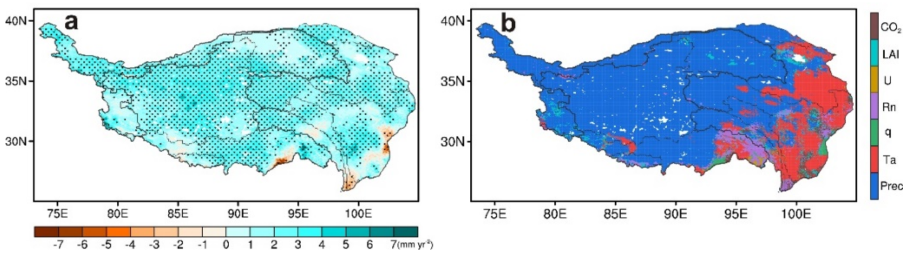

Figure 1. Spatial pattern of (**a**) the trend in ET during 1982-2016 and (**b**) dominated drivers across TP

Keywords: *Land evapotranspiration, PML_V2, sensitivity analysis, attribution, Tibetan Plateau*

Generation and delivery of gap-free Landsat-based monthly actual evapotranspiration for Australia using Google Earth Engine

Tim R. McVicar[1*], **Jamie Vleeshouwer**[2], **Thomas G. Van Niel**[3], **Juan P. Guerschman**[1], **Jorge L. Peña-Arancibia**[1], **Yun Chen**[1] **and Matthew P. Stenson**[2]

[1] *CSIRO Land and Water, Black Mountain, Australian Capital Territory, Australia*
[2] *CSIRO Land and Water, Dutton Park, Queensland, Australia*
[3] *CSIRO Land and Water, Floreat, Perth, Western Australia, Australia*
Email: Tim.McVicar@csiro.au

Abstract: Actual evapotranspiration (AET) is often the largest 'consumptive' component in the catchment water-balance and is also central to the surface energy balance and the carbon balance. As high spatial resolution AET is challenging to estimate across regional-to-continental scales, in a TERN funded project using Google Earth Engine (GEE) infrastructure and available data, we developed a monthly Landsat-based (30 m) gap-free Australia-wide AET product using the CMRSET reflective remote sensing algorithm. To achieve the abovementioned AET product characteristics required that the calibration of CMRSET was (i) updated to the most recent MODIS collection; and (ii) performed for the first-time using Landsat, VIIRS and Sentinel-2 imagery. Additionally, (iii) to provide a gap-free AET product that is analysis-ready ('good-to-go' from a user-perspective) we filled gaps in the Landsat series via Landsat-MODIS and Landsat-VIIRS blending. Calibration of the four abovementioned reflective sensors were conducted using daily latent heat observations from the TERN OzFlux network. For the 29 flux towers the relative Root Mean Squared Error (rRMSE) ranged from 0.16 (Sentinel-2) to 0.27 (VIIRS) with the coefficient of determination (R^2) ranging between 0.96 (Sentinel-2) to 0.92 (VIIRS). Additionally, independent evaluation of the newly calibrated MODIS CMRSET AET product was performed by assuming steady-state and closing the long-term (> 5-years) catchment water balance using Bureau of Meteorology gridded precipitation (P) and observed streamflow (Q) data. The resulting water balance estimate of AET ($AET_{WB} = P - Q$) was generated for 638 unimpaired catchments across Australia, and comparing AET_{WB} with the MODIS CMRSET AET estimates yielded a rRMSE of 0.24 and a R^2 of 0.76. Using GEE over 141,000 Landsat images totalling over 75 Tb were processed to develop the TERN AET product. The Landsat-based AET estimates can be viewed in a purpose-built GEE app available at https://tern-landscapes.earthengine.app/view/cmrset-landsat-v21. The data can be freely accessed for user-defined points and polygons from this GEE app in both depth units (daily average mm/month or total mm/month) and volumetrically (L/month, ML/month or GL/month). For more details about the TERN AET product see https://www.tern.org.au/news-australia-wide-aet-data/. Geo-modellers from numerous disciplines (e.g., hydrologists, climatologists, agronomists, ecologists) can now access the monthly 30 m AET data for any part of the Australia continent.

Keywords: *Actual evapotranspiration, Landsat, geo-model, Google Earth Engine, remote sensing*

Cutting-edge remote sensing to underpin water resource assessments

Jorge L. Peña-Arancibia [a], **Yingying Yu** [a], **Mobin-ud-Din Ahmad** [a], **Mohammed Mainuddin** [a] **and Tim R. McVicar** [a]

[a] *CSIRO Land and Water, Black Mountain Science and Innovation Park, ACT 2601, Australia*
Email: jorge.penaarancibia@csiro.au

Abstract: Water resource use is on an unsustainable trajectory in many large river basins in arid and semi-arid regions. In agricultural basins, this is chiefly because of the increased reliance on surface water and groundwater for irrigation to meet growing demands for food and fibre. The impact of irrigation on surface water and groundwater resources has been difficult to quantify at policy-relevant scales. Satellite Remote Sensing (RS) provides an opportunity to assess irrigation dynamics and water use at resolutions amenable for detailed modelling and decision making from farm to regional scales. Crop types and associated water use can be quantified by using publicly available RS data with machine learning and other data-driven techniques. This talk showcases recent research which used Landsat (30 m) and MODIS (500 m) reflectance data to estimate water use and crop types in northwest Bangladesh (~34,540 km^2, Peña-Arancibia et al., 2021), the irrigated Indus Basin in Pakistan (~160 000 km^2, Peña Arancibia and Ahmad, 2020) and the Murray-Darling Basin (~1 million km^2, Peña Arancibia et al., 2021). The large amount of data and processing required computational power which was harnessed through the cloud-based geospatial processing and peta-bite repositories of analysis ready data implemented by Google Earth Engine. Common issues and potential solutions related to using satellite reflectance data in these cloud-affected regions are discussed, as are the possibilities of implementing scalable monitoring tools like CSIRO's Earth Analytics Science and Innovation platform (EASI), which enhances the capacity to process and integrate big RS data with other geospatial information and models using a friendly interface through Jupyter Notebooks.

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Keywords: *Actual evapotranspiration, irrigation water use, crop coefficient, crop types*

EXTENDED ABSTRACT ONLY

Assessment of ecosystem resilience in Central Asia

Jingxiu Qin [a,b]

[a] *State Key Laboratory of Desert and Oasis Ecology, Xinjiang Institute of Ecology and Geography, Chinese Academy of Science, Urumqi, 830011, Xinjiang, China*
[b] *University of Chinese Academy of Science, Beijing, 100049, China*
Email: qinjingxiu17@mails.ucas.ac.cn

Abstract: Climate change has a profound impact on ecosystem stability. Recent studies still have insufficient understanding of the response of vegetation to climate change, especially the response of vegetation to short-term climate anomalies. Therefore, the quantitative evaluation of ecosystem resilience is of great significance.

Based on normalized difference vegetation index (NDVI) and the meteorological data, this study used an autoregressive model to conduct a quantitative assessment of the ecosystem resilience and resistance, and analysed the relationship between resistance, resilience and land cover. Furthermore, a new method was developed to identify ecologically fragile regions.

The result showed that the resilience and resistance of the Central Asia ecosystem to short-term climate change are generally low (Fig. 1-1). When tree cover below 5%, vegetation resilience varied from low to relatively low and then to high as the fraction of non-tree cover increased (Fig. 1-2a). The areas with high resilience were no longer present when the fraction of non-tree cover increased from 40% to 80%. Only for very high fractions of non-tree cover (>90%) did the resilience show high levels. When tree cover was less than 10%, the overall resilience was low. However, the resilience became high when the tree cover was 15%–30% and the non-tree cover was 40%–80%. Resilience increased with tree cover. Analysis of the drought-resistance metrics as a function of fractions of tree cover, non-tree cover and bare soil cover showed that high resistance was distributed in two areas: (1) areas where the bare soil fractions were above 60% and tree cover fractions were below 10%, and (2) areas with 10%–30% tree coverage and 40%–80% of non-tree coverage (Fig. 1-2b). The resistance metric increased with tree cover when the bare soil fractions were below 60%, consistent with the resilience. The temperature-resistance metrics showed patterns similar to those of drought resistance when analysed as a function of vegetation cover (Fig. 1-2c). Therefore, the relationship between resistance, resilience and vegetation cover was nonlinear. If there were too many or too few trees, the stability of the ecosystem was compromised. The mixture of grassland and trees was more stable than relatively single vegetation, but the percentage of tree cover must fall within 10%–30%. The main control factor affecting the stability of the Central Asian ecosystem was water (Fig.1-3a), and the areas with high sensitivity and low resilience were defined as an ecologically fragile area. Ecologically fragile areas were found in transition areas from vegetation to non-vegetation (Fig.1-3b). This study helps to better understand and quantify vegetation resilience and resistance while explicitly taking short-term climate anomalies into account. The results provide more detailed guidelines for strengthening ecosystem management.

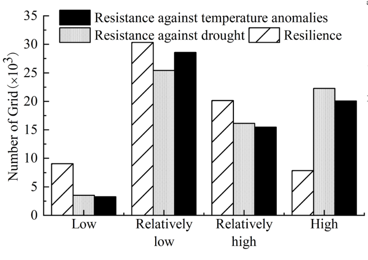

Fig. 1-1

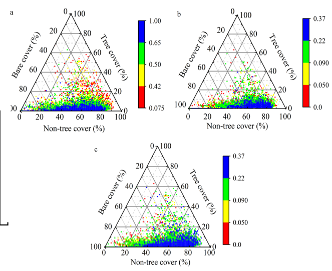

Fig. 1-2

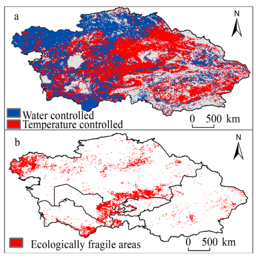

Fig. 1-3

Fig. 1-1 The resilience and resistance of the Central Asian ecosystem. **Fig. 1-2** Relationship between resilience, resistance, and vegetation cover. Vegetation resilience (a), vegetation resistance against drought (b), vegetation resistance against temperature anomalies (c). **Fig. 1-3** Spatial distribution of the control factors on vegetation anomalies (a) and ecologically fragile areas (b) in Central Asian.

Keywords: *Ecosystem, resilience, resistance, vegetation cover, Central Asia*

Fusion of high-resolution remote sensing soil moisture data to better estimate evapotranspiration in China

P. Song

Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, The Chinese Academy of Sciences, Beijing 100101, China
Email: songpl@igrnrr.ac.cn ; yongqiang.zhang2014@gmail.com

Abstract: Evapotranspiration (ET) is a key hydrologic variable linking the Earth's water, carbon and energy cycles. Remote sensing (RS) datasets are usually identified as essential inputs for driving ET processes at large spatial scales. Since ET is an earth-surface process mainly controlled by integrated effect from the amount of water available in soils, the demand of water vapor in the atmospheric column, and the incoming long-wave and short-wave radiation from the sun and the cloud, a large number of RS ET models have employed surface energy models for calculating ET from continental to global domains. However, few of these models have included soil moisture among their input parameters. Instead, most of them exploited atmospheric vapor pressure deficit or soil temperature as the proxy for quantifying water availability in the soil. This may degrade accuracy and utility of model outcomes.

Based on an improved downscaling methodological framework on AMSR-E/AMSR-2 passive microwave surface soil moisture product in our previous study (Song et al. 2021), we have developed a 1-km resolution daily surface soil moisture data product all over China. In this study, we investigated the potential capability of this product on improving the ET estimation accuracy of a recently developed diagnostic water-carbon coupled biophysical model based on the Penman-Monteith equation, i.e. the PML-V2 model (Zhang et al. 2019). In this model, the total evapotranspiration is conceptually divided into three components including soil evaporation, vegetation transpiration, and evaporation of precipitation intercepted by the vegetation. To calculate the soil evaporation, an input parameter *f* is required and is originally represented as a function of accumulated precipitation and soil equilibrium evaporation in the recent month or half, based on meteorological features from the GLDAS V2.1 reanalysis datasets. As this parameter is actually defined to quantify the soil wetness degree, we have used our downscaled RS soil moisture datasets to recalculate it, as $f = \frac{SM_0 - SM_{min}}{SM_{max} - SM_{min}}$. SM_0 herein denotes soil moisture content of a 1-km pixel at one certain time, whilst SM_{min} and SM_{max} respectively denote the theoretical minimum and maximum thresholds on evaporative efficiency of local soils and are related to soil texture properties. All other technical processes and data input configurations are inherited from our previous study of Zhang et al. (2019). Both the original PML-V2 and the SM-constrained new model (hereafter referred to as PML-V2.1) were applied for calculating 8-day averaged ET at all 1-km pixels in China throughout the years of 2010, 2014, and 2016. The estimated ET based on PML-V2 and PML-V2.1 were respectively validated using corresponding in situ observations from 8 national-level ET flux sites which are all characterized by crop land covers.

The validation results show that the PML-V2.1 based ET outcomes is in better correspondence with the in-situ observations (RMSE ≈ 0.974 mm/day) compared with the original PML-V2 outcomes (RMSE ≈ 1.178 mm/day). This has preliminarily confirmed the feasibility of using high-resolution RS soil moisture data for improving ET modelling performance. The following studies are encouraged on evaluating the performance of the PML-V2.1 model in a wider range of flux sites on various land cover types.

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Keywords: *Evapotranspiration (ET), soil moisture, flux site*

The impact of climate change and human activities on the Aral Sea Basin over the past 50 years

Xuanxuan Wang [a]

[a] *State Key Laboratory of Desert and Oasis Ecology, Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences, Urumqi 830011, China*
Email: wangxuanxuan17@mails.ucas.edu.cn

Abstract: As a region with severe water crisis and complicated water politics in Central Asia, the water resources and ecological environment of the Aral Sea have quickly become a hot topic for scholars in the world. The long-term dynamics of the Aral Sea are affected by climate change and human activities, while the shrinking rate of the Aral Sea has slowed in recent years, and the underlying causes and the degree of influence of climate factors and human activities on the Aral Sea have not been reported yet.

In this work, based on the extreme-point symmetric mode decomposition (ESMD) method and the multiple linear regression model, we analyzed the changing of the Aral Sea from 1960 to 2018, and detected the time for slowdown of retreat, then explored the driving forces. The results show that the Aral Sea retreated rapidly from 1960 to 2004, and the shrinking rates of water surface area, water volume and water level were 1,087.00 km^2/year, 25.07 km^3/year, and 0.56 m/year, respectively (Figure 1a,b); the retreat has slowed since 2005, with the shrinking rates being 760.00 km^2/year, 2.86 km^3/year, and 0.38m/year, respectively. At the same time, the area of water bodies surrounding the Aral Sea increased due to the agricultural drainage water (Figure 1c,d). The oscillation periods of water level in the Aral Sea are 2.1a, 7.6a and 29.5a, of which 29.5a is the main period of oscillation. The trend residual RES indicates that water level shows a non-linear downward trend, and the degree of fluctuation has decreased significantly after 2005.

The impact of human activities on the Aral Sea is more significant than that of climate change. Overall, the increased upstream runoff, reduced water withdrawal, and rise in water delivery to the Aral Sea has led to a slowing down of the sea's notorious shrinkage. The findings will provide a decision-making reference for the management and protection of the Aral Sea and the formulation of water resources policies. It is also of great significance to improve the efficiency of water resources utilization and the reform of crop planting structure in the basin.

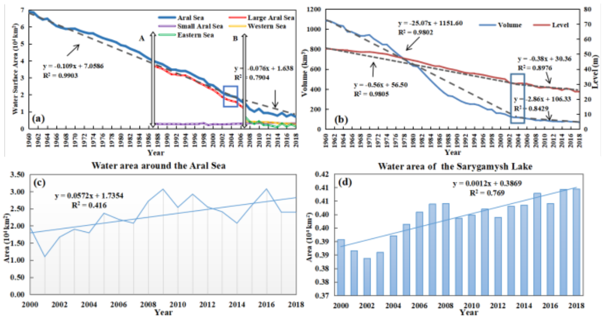

Figure 1. Trends in the Aral Sea water surface area (a) and water volume and water level (b) from 1960 to 2018, changes in water area around the Aral Sea (c) and at Sarygamysh Lake (d) from 2000 to 2018.

Keywords: *Dynamic change, land cover, runoff, water withdrawal, Aral Sea*

Bushfire impacts on evapotranspiration and water balances in southeast Australia

Zhenwu Xu [a,b] **and Yongqiang Zhang** [a]

[a] *Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, CAS, Beijing, China;* [b]*University of Chinese Academy of Sciences, Beijing, China*
Email: zhangyq@igsnrr.ac.cn

Abstract: While bushfires are often regarded as a vital trigger that alters the partitioning of hydrological fluxes, their role in evapotranspiration and other water balance components remains poorly quantified, especially over southeast Australia where impacts of frequent bushfires and huge climate variability overlap (Nolan et al., 2015).

Here, we quantified bushfire-induced water balance changes by comparing differences of anomalies between paired catchments, and improved the eventual estimations by modelling rainfall-storage relationships among anomalies. In application, using high-quality precipitation data, remoted-sensed evapotranspiration, observed streamflow and terrestrial water storage derived from water balance, we test the method for eight forested headwaters impacted by the 2009 Victorian Bushfires in Australia with multiple burned areas (12~89 %),

Actual evapotranspiration (ET) averagely declined by 26 ± 18 mm yr^{-1} and streamflow increased by 62 ± 25 mm yr^{-1} during the post-fire decade. The ET declining response (20~170 mm yr^{-1}, Fig. 1a) recovered after the first event year, while the streamflow increasing response mostly peaking in the second or third year (96~321 mm yr^{-1}, Fig. 1b), suggesting the temporal asynchronization of hydrological responses and recovery from the fires. After excluding rainfall's impact, we estimated that on average 60 ± 22 % of bushfire-induced streamflow increases came from a reduction in catchment water storage.

The bushfires played a dominant role in post-fire ET changes, leading to the ET decline in the first three years after the fire. The role of bushfires is also more important than that of climate in post-fire streamflow increases in most catchments. However, the bushfire-induced water storage decline was quickly offset by a wetter climate after the bushfires (Fig. a3). Catchments with larger burned areas tend to experience larger changes.

Overall, this study demonstrated the potential of paired catchment method in detecting changes in catchment ET and water balances and provided robust quantifications of the bushfire impact on hydrological fluxes as well as a comparison of its role to climate variability.

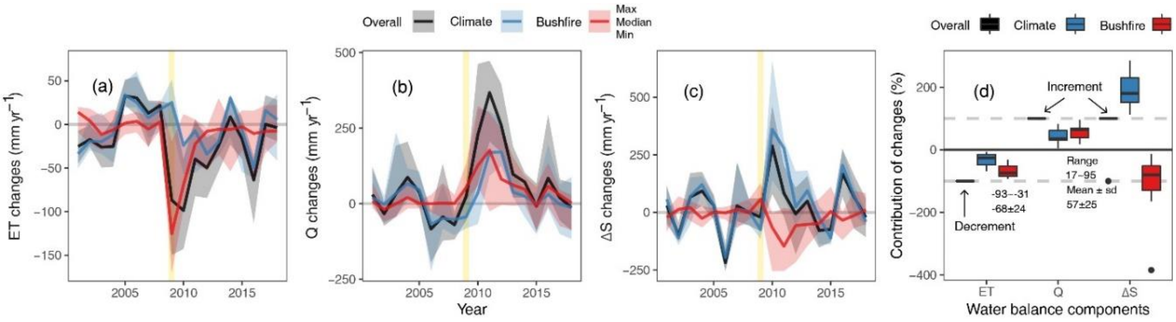

Figure 1. Contributions of 2009 Victorian Bushfires and climate on the annual variability of water balance components across eight forested Australian headwaters. Evapotranspiration, ET, streamflow, Q, and terrestrial water storage change, ΔS. In subplot (d), the boxplot of overall changes shrinks into one black segment to indicates the polarity (100% or -100%, increment or decrement). The range, mean and standard deviations of the contribution of bushfire-induced ET changes and Q changes, are computed by the decadal-averaged results for all catchments.

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Keywords: *Bushfire, evapotranspiration, water balance, climate, paired catchments*

A generalized complementary principle approach with atmospheric stability corrections for estimating sub-daily evaporation

Lu Zhang[a], **Shujing Qin**[b] **and Wilfried Brutsaert**[c]

[a] *CSIRO Land and Water, Canberra ACT 2601, Australia*
[b] *State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, Wuhan 430072, China.*
[c] *School of Civil and Environmental Engineering, Cornell University, Ithaca, New York, USA*
Email: lu.zhang@csiro.au

Abstract: At daily or longer time scales, the generalized complementary principle has been shown to provide accurate estimates of evaporation. However, validity of the complementary principle has not been thoroughly tested at sub-daily time scale. In this study, a generalized implementation of the complementary principle approach combined with the Monin-Obukhov similarity theory is tested for estimating sub-daily land surface evaporation. The performance of the method was evaluated against measured 30-min evaporation rates using eddy covariance-system at four Australian flux sites under a range of surface and climatic conditions. The atmospheric evaporative demand or apparent potential evaporation, one of the key variables in the complementary principle, was estimated using the Penman equation with atmospheric stability correction included and the influence of daytime instability increases the apparent potential evaporation by 36% compared with the neutral conditions. The parameter of the complementary principle model remained approximately constant during daytime, exhibiting self-preservation. The estimated 30-min evaporation values were in good agreement with measurements with a mean R^2 of 0.93 and a bias of 6% on average. The complementary relationship assumption was found to be valid at sub-daily timescale and the effect of atmospheric stability is important for estimating sub-daily evaporation. The results showed that the generalized implementation of the complementary principle with atmospheric stability correction included can accurately estimate 30-min evaporation during daytime (defined as non-negative available energy). The present method is robust with consistent performance in both calibration and validation periods.

Keywords: *Generalized complementary principle, atmospheric stability corrections, sub-daily evaporation, flux measurements*

A comparative study of three stomatal conductance models for estimating evapotranspiration in a dune ecosystem in a semi-arid region

Yongzhi Bao[a], Tingxi Liu[a], Limin Duan[a] and Xin Tong[a]

[a] *College of Water Conservancy and Civil Engineering, Inner Mongolia Agricultural University, Hohhot, 010018, China*
Email: byz6618@163.com

Abstract: Evapotranspiration (ET) is a key part of eco-hydrological processes and is synthetically controlled by meteorological conditions, physiological and ecological characteristic of vegetation, and underlying surface conditions (Jung et al. 2010). Accurate characterization of the ET process is of great significance for understanding the carbon, water, and energy cycles and their responses to climate and environmental changes. An understanding of the ET process is particularly important for arid and semi-arid regions as these regions occupy ~40% of the global terrestrial surface. In addition, the arid and semi-arid regions are vulnerable to ecological and environmental problems such as water deficits, land desertification, and frequent extreme climate (Zhao et al. 2016). Stomatal conductance simultaneously regulates photosynthesis and transpiration, and the representation of stomatal conductance in models is important for accurately estimating ET. However, the optimal model for estimating stomatal conductance and ET of a dune ecosystem has yet to be identified. This study coupled three stomatal conductance models, i.e. the Stannard (ST), Jarvis-Stewart (JS), and Ball-Berry (BB) models, with the Shuttleworth-Wallace (SW) model to estimate ET for a mobile dune ecosystem in the Horqin Sandy Land, North China. These models were calibrated and validated using eddy covariance (EC) measurements taken during the growing season between 2013–2018.

The results indicated that the SW-BB model showed better performance in comparison to the SW-JS and SW-ST models at half-hourly and daily timescales. The stomatal conductance models incorporating soil moisture (SM) content generally showed better performance during the extreme drought period, with the rank of the three models according to performance being: SW-BB > SW-JS > SW-ST. The models showed the highest sensitivity to SM when incorporating the effect of SM on stomatal conductance, indicating that SM has an important effect on stomatal conductance and ET. The results of this study indicate that of the models assessed, the Ball-Berry stomatal conductance model coupled with the SW model is optimal for estimating ET in dune ecosystems with sparse vegetation. This study could provide a theoretical basis and technical support for water management and vegetation restoration in desertification areas.

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Keywords: *Evapotranspiration, sandy land, canopy stomatal conductance, eddy covariance*

A method for determining the suitable scale of oasis and cultivated land based on ecological health assessment in arid area

Lina Hao [a] **and Xiaoling Su** [b]

[a] *College of Water Conservancy & Civil Engineering, Inner Mongolia Agricultural University, Hohhot, 010018, China*
[b] *College of Water Resources and Architectural Engineering, Northwest A& F University, Yangling, 712100, China*
Email: haolina0520@163.com

Abstract: A suitable oasis scale and a cultivated scale are important for water resources management in arid regions. With social-economic development and population growth, increasing water resources are being used for agricultural production and are, in turn, being depleted which are needed for natural oasis ecosystems (Cheng et al. 2014). In this situation, the ecological scale is not sufficient to support the sustainable development of the oasis. Thus, it is essential to determine a reasonable size of ecological vegetation area and of agricultural cultivation area in order to ensure the sustainable development of the oasis (Zhao et al. 2016).

In arid and semi-arid regions, water resources play a vital limiting role in maintaining production and ecological environment of an agricultural oasis. Agricultural production relies on the water withdrawn from rivers or on pumped groundwater, and the natural vegetation outside the agricultural oasis, which serves an ecological defense function (such as shrubs and grasslands), is completely dependent on the capillary rise of groundwater. Therefore, we defined the oasis ecological health from the perspective of water resources, and an index system was developed for illustrating the criteria for the oasis ecological health. The index system considered groundwater depth, ratio of farmland shelterbelt, vegetation coverage status, and occurrence frequency of strong winds as ecological health evaluation indicators. The indicators were weighted, based on an analytical hierarchical process (AHP).

Another factor that can indicate ecological health is the effective vegetation coverage, which refers to the proportion of vegetation coverage in which soil and water conservation of oasis ecosystem reaches an optimal state. Based on wind-sand dynamics theory, the sand transport rate changes with the change of vegetation cover (Li 2008). Then, an approach to calculate a suitable oasis scale and a cultivated scale model was developed by combining water-heat balance theory and effective vegetation coverage with ecological health assessment (WHBEHA).

Results revealed that the most suitable ecological area and cultivated area in the middle reaches of Heihe River basin under different hydrologic years were 367~501 km^2 and 1468~2004 km^2 and simultaneously the suitable oasis areas were 1836~2505 km^2. Compared with the calculated current oasis scale and suitable scale and cultivated scale based on the oasis water-heat balance and oasis circle theory (WHBOCT), the proposed method considers factors that affect ecological health of arid areas and is therefore more suitable.

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Keywords: *Ecological health assessment, arid area, cultivated land*

Study on transpiration and water consumption of artificial poplar in Horqin Sandy Land based on Shuttleworth-Wallace model

Tianyu Jia [a]

[a] *College of Water Conservancy and Civil Engineering, Inner Mongolia Agricultural University, Hohhot 010018, China*
Email: 610296924@qq.com

Abstract: Transpiration is a key link in the process of ecohydrological cycle. It plays an important role in ecological civilization construction of fragile desertification areas to clarify the process and law of water consumption by transpiration of artificial poplar (Dolman et al. 1993).

The study was carried out in the Horqin Sandy Land in the southeastern margin of Tongliao, Inner Mongolia Autonomous Region. The vegetation of studied was the main tree species in this area -- artificial poplar. Based on the monitoring data of physiological characteristics of artificial poplar during the whole growth period and the measured data of meteorological factors in vegetation community growth environment, P.G. jarvis model was used to simulate the relationship between stomatal conductance indices monitored by photosynthesis test and environmental factors to established the optimal stomatal conductance models in the early, middle and late stages of vegetation growth (Jarvis et al. 1976). Then based on the calculation formula of boundary layer resistance provided by A.J. Dolman, we combined the simulation results of stomatal conductance at each growth stage and LAI measurement results of the study area, and calculated the canopy boundary resistance of poplar in the whole growth period. On this basis, we improved the original simulation method of canopy boundary resistance in Shuttleworth-Wallace model, and calculated the evapotranspiration of artificial poplar groups in the whole growth period. Finally, the actual transpiration of poplar was measured with thermal dissipation probe, and the simulation results and optimization degree were verified by it. obtain the transpiration and water consumption capacity of artificial poplar groups in different growth stages.

The result shows that. In the early, middle and late growth stages, there were 27 kinds of simulation models (9 simulation models were established in each stage). The best optimal simulation model was selected from all of simulation results, and the determination coefficient R2 was 0.964 ($P<0.01$), 0.560 ($P<0.05$) and 0.963 ($P<0.01$), respectively. The improved Shuttleworth-Wallace model has high simulation accuracy for the transpiration water consumption of poplar groups area in the whole growth period. The maximum relative error between simulated and measured value of stem flow was less than 10% during the whole growing season.

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Keywords: *Horqin Sandy Land, P.G. Jarvis model, Shuttleworth-Wallace model, Thermal dissipation probe, Environmental factors*

Eco-hydrological model for grassland lacking historical measurements

Li Mingyang [a]

[a] *College of Water Conservancy and Civil Engineering, Inner Mongolia Agricultural University, Hohhot，010018, China*
Email: myli1993@qq.com

Abstract: Reports on eco-hydrological models for semi-arid steppe basins with scarce historical data are rare. To fully understand the eco-hydrological processes in such areas and accurately describe the coupling and mutual feedback between ecological and hydrological processes, a distributed eco-hydrological model was constructed, which integrates multi-source information into the MY Eco-hydrology (MYEH) model.

MYEH model is a bidirectional coupling eco-hydrological model for steppe inland river basins in arid and semi-arid regions, which is driven by meteorological data and developed by Dr. Mingyang Li and Prof. Tingxi Liu. In order to get more support from researchers and better improve the model, the model will be released as open source and gradually optimized and updated. The MYEH model mainly includes evapotranspiration, runoff, confluence, grazing disturbance, carbon and nitrogen cycle, etc. It absorbs the advantages of various existing ecological models, hydrological models, as well as the framework and algorithm of eco-hydrological models. Now, we have launched 3 modules including evapotranspiration module, flow generation module, snow process and confluence module.

Evapotranspiration (ET) module can be divided into three parts: judgment, simulation, and validation. The judgment part is used to distinguish the specific types contained in ET (Balin et al. 2010). The simulation part is to simulate ET of 3hr scale. The inspection part is to use the existing products and measured data to test the downscaling ET results.

The function of the flow generation module is to calculate the flow yield of each grid in the basin in unit time by inputting temperature, precipitation, actual evapotranspiration (calculated by the evapotranspiration module of MYEH model), grid area and other data. The distribution function of water storage capacity of a water storage unit is used in the calculation of soil water unit of runoff generation module. Unlike HYMOD, the evaporation rate of the soil water reservoir is calculated using the evapotranspiration module of the MYEH model.

The confluence module calculates all grid simulated runoff in the basin according to the river direction generated by the basin elevation, river width, river length, roughness and other characteristics. The main work of the confluence module is to summarize and calculate the runoff depth of each grid in the basin according to the flow direction of the river in unit time, which is mainly divided into three units: input, process variable calculation and debugging output.

Simulation results in Xilin River basin show that the MYEH model developed for steppe basin has good ability of simulating eco-hydrological process and flood prediction, and has great development prospect in the subsequent research.

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Keywords: *MY Eco-hydrology (MYEH) model, flood prediction, hydrology process*

Spatial and temporal variability of carbon dioxide, methane and nitrous oxide emissions in a eutrophic shallow lake

Guohua Li

[a] *College of Water Conservancy and Civil Engineering, Inner Mongolia Agricultural University Hohhot,010018. China*
Email：liguohua@emails.imau.edu.cn

Abstract: Freshwaters are important sources of greenhouse gases(GHGs) to the atmosphere, knowledge of GHGs(CO_2, CH_4, N_2O) concentration and emission of shallow eutrophic lakes in cold and arid areas is very limited. In this study, we focus on the concentrations and fluxes of carbon dioxide, methane and nitrous oxide during winter, summer and autumn.

In order to better understand the GHG concentrations and diffusive fluxes in a large shallow lake with extensive macrophyte communities (Phragmites australis, Typha latifolial), with several submerged plants which are unevenly distributed over the lake area, our sampling program covered almost the entire lake open area. The concentration and fluxes of GHGs displayed significant spatiotemporal variability, winter is significantly larger than other seasons. CO_2 concentration was 265±80μmol L^{-1}, while in summer (June-August)) it was 28±22μmol L^{-1} and in autumn（September-November）it was 29±21μmol L^{-1} respectively, the average CH_4 concentration was 5.1±5.6μmol L^{-1} in winter, and in summer was 2.6±1.6μmol L^{-1} and in autumn was 1.1±0.7μmol L^{-1}. The average N_2O value in January was 60±36 nmol L-1, while in summer it was only 9.7±4.6 nmol L^{-1} and in autumn was17±6 nmol L^{-1}.

Meanwhile annual carbon budget across air–water interface in Lake Ulansuhai was estimated. This study will enrich the carbon database of northern lakes of China in the global GHGs emission.

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Keywords: *Greenhouse gases emission, spatiotemporal variability, Lake Ulansuhai, entrophication*

Carbon uptake and water vapor exchange in mobile sand dunes in semi-arid regions

Xia Li [a]

[a] *College of Water Conservancy and Civil Engineering, Inner Mongolia Agricultural University, Hohhot 010018, China*
Email: lx1994@emails.imau.edu.cn

Abstract: Carbon dioxide and water vapor exchange processes are closely related to the regional carbon-water balance (Tian et al. 2016). Therefore, it is important to quantify the magnitudes of Carbon and water fluxes, and uncover the controlling factors and mechanisms of semi-arid ecosystems, which would benefit both earth system model improvement and climate change prediction (Sun et al. 2019). This study employed a continuous 6-year (2013-2018) observational dataset collected using an eddy-covariance (EC) technique at the Agula Ecohydrological Experimental Station to explore the net ecosystem CO_2 exchange (NEE), gross primary production (GPP), ecosystem respiration (Reco), evapotranspiration (ET) and water use efficiency (WUE) variability for mobile dunes in China's Horqin Sandy Land.

On the daily scale, the NEE minimum was -0.08 to -0.03 mgCO_2 m^{-1} s^{-1} in the early growing stage (April-May). The NEE reached a minimum value in the middle growing stage (June-August), with the largest daytime CO_2 uptake value in 2018 (0.21 mgCO_2 m^{-1} s^{-1}) and the smallest in 2016 (-0.08 mgCO_2 m^{-1} s^{-1}). The daily variation of ET was single-peaked. It tends to be close to zero at night and tends to increase and then decrease during the day time. The ET value at mid-growing stage in 2018 was significantly greater than in other years, with a maximum of 3.51 mm d^{-1}. Daytime NEE was significantly correlated with photosynthetically active radiation (PAR). It was also regulated by environmental factors such as saturated vapor pressure deficit (VPD) and temperature (Ta).

On the seasonal scale, both Reco and GPP reaching a maximum during the mid-growing stage. NEE behaved as a carbon sink during the growing seasons of 2013, 2014, 2017 and 2018. The intra-annual variation was more consistent. The total NEE was 2.54 and 3.28 gCO_2 m^{-2} d^{-1} in 2015 and 2016, exhibiting a carbon source. In the mid-growing stage accounted for 49%-63% of the entire growing season. The daily ET from 0.08 to 2.84 mm·d^{-1}. The annual cumulative ET was highest in 2018 (258.01 mm) and lowest in 2014 (126.62 mm). The daily ET peak had a strong response relationship with precipitation. Reco was not significantly correlated with NEE. GPP was significantly correlated ($P<0.05$) with NEE and Reco with R^2 of 0.46 and 0.78. GPP had a strong linear correlation with ET ($P<0.05$), with R^2 greater than 0.5 in 2013, 2017, and 2018.

The seasonal variation of WUE varied over the 6-year observation period. The monthly mean WUE varied between 2.34 and 13.62 gCO_2 kg^{-1} H_2O. The variation of water use efficiency was greater in summer than in autumn due to the influence of drought. The water use efficiency was influenced by the combination of net radiation, air temperature, and saturated water-air pressure difference, and its degree of influence showed a large variability under different vegetation conditions.

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Keywords: *Semi-arid regions, Net ecosystem CO_2 exchange (NEE), Evapotranspiration (ET), Water use efficiency (WUE)*

Characteristics and environmental driving factors of water transformation in Inner Mongolia steppe watershed

Fang Lijing [a] and **Gao Ruizhong** [a]

[a] *College of Water Conservancy and Civil Engineering, Inner Mongolia Agricultural University, Hohhot, 010018, China*
Email: 1329867839@qq.com

Abstract: Inner Mongolia Plateau steppe watershed was taken as one of the ecological barriers in Chinese inland. The evolution of water resources was very important for the development of social-economy and the protection of eco-environment in the steppe watershed.

In recent years, there were significant changes on the hydrological process because of the impact of climate change and human activities in the Mongolia plateau inland basin (Zhang et al. 2019). Water resources shortage was affecting the ecosystem health of grassland in these areas. So, there is important significance to the sustainable development of the basin by effective protection and understanding transfer rules of water resources (Yuan et al. 2019). The environmental hydrogen and oxygen isotope technology has been widely applied in the research of hydrology and water resources (Gu et al. 2017). More information about the internal process of water cycle can be obtained and greatly improves the understanding of the interaction between "atmosphere-precipitation-surface water-groundwater" by using the technology.

Balaguer River watershed in the inland steppe basin was selected as typical study area, in which 254 water samples of precipitation, river, and shadow groundwater were collected during wet-season and dry-season of 2018-2019, and the physical-chemical indicators, δD, and $\delta^{18}O$ of samples were tested. The stable isotope technology, mathematical statistics, and the inverse distance weighting method were adopted to explain the stable isotope composition, spatial-temporal variation and impact factors. Moreover, the d-excess and the isotopic mixing ratio formula were used to reveal conversion characteristics of different water and identify their environment driving variables.

The results show that: 1) δD and $\delta^{18}O$ of precipitation, river and shallow groundwater were higher in wet season than in dry season. 2) The environment driving factors of different water transformation in the steppe watershed were air temperature, altitude and groundwater depth. There was significantly negatively correlated relationship between river δD and altitude, and the same to the δD and $\delta^{18}O$ of groundwater. δD and $\delta^{18}O$ of groundwater fluctuated significantly in the area that groundwater depth was less than 10m, and the other area values was stable. There was significantly positively correlated relationship between precipitation $\delta^{18}O$ and air temperature. 3) The d-excess in wet season was higher than dry season, and show the decreased distribution characteristic from southern to northern in the study area. 4) More than 50% river in upper stream came from precipitation. More than half river converted to groundwater. It existed different recharge-drainage relationships between surface water and groundwater in different river stage. The research results could be taken as a technical reference for protection and restoration of regional grassland ecological environment, exploitation and utilization of water resources and study of watershed eco-hydrology.

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Keywords: *Plateau inland river, steppe watershed, hydrogen and oxygen stable isotopes, conversion relationship, water resource environment*

Effects of animal grazing on vegetation biomass and soil moisture on a typical steppe in Inner Mongolia, China

Xi Lin[a], Hongbin Zhao [b] and Shengwei Zhang [a, c, d]

[a] *College of Water Conservancy and Civil Engineering, Inner Mongolia Agricultural University, 010018 Hohhot, China.*
[b] *College of Life Sciences, Inner Mongolia Agricultural University, 010018 Hohhot, China.*
[c] *Inner Mongolia Autonomous Region Key Laboratory of Big Data Research and Application of Agriculture and Animal Husbandry, 010018 Hohhot, China.*
[d] *Key Laboratory of Water Resources Protection and Utilization of Inner Mongolia Autonomous Region, 010018 Hohhot, China*
Email: zsw@imau.edu.cn (Shengwei Zhang)

Abstract: Grasslands play a very important role in the water and carbon cycle of arid and semi-arid areas, where they are the main type of steppe globally (Y. Zhang et al., 2020). With this said, research into grassland ecological processes mostly consists of single-factor controlled experiments such as precipitation, temperature or grazing, and few studies have investigated the effects of synergistic interactions between multiple factors on grassland hydrological, soil and vegetation processes(Lyu et al., 2020).

Based on previous studies on the effects of grazing on biomass and soil environments (Erb et al., 2018; Yamazaki, 2020), we set up a prohibited grazing area in a typical area of the Xilingole Steppe in Inner Mongolia, China. Vegetation (species richness (SR), above-ground biomass (AGB), below-ground biomass (BGB), etc.), precipitation and the soil moisture of 5cm, 10cm, 15cm and 30cm depths were observed continuously from 2015 to 2018.

The results indicate that the species number in areas where grazing is prohibited is higher than where it is grazed, and the number and species of dominant species changes with grazing prohibition time. The AGB and BGB of prohibited areas is higher than grazed areas, and the variance rate of AGB increased rapidly (20% and 45%) at the first two years and then stabilized (52% and 55%), but BGB's variance rate increased slowly from 12% to 20%. The soil moisture content in the study area is higher in the surface layer than in the deeper layers. In the grazing prohibition zone, the above ground biomass (AGB) and belowground biomass (BGB) were both significantly correlated with volumetric water content (VWC) at the 0.01 level. In grazing areas, there was no significant correlation between AGB and soil moisture, and the coefficient of determination between BGB and VWC was 0.6127 ($p<0.01$). SR didn't have a significant relationship with soil moisture but indirectly response to it through BGB, especially in prohibited site.

These results are important for understanding water cycle processes, grazing management, and address food security issues across steppe in arid and semi-arid regions.

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Keywords: *Typical grasslands, ecohydrology, species richness, precipitation, soil moisture*

An ecological stability-oriented model for the conjunctive allocation of surface water and groundwater in oases in arid inland river basins

Zixu Qiao [a], Long Ma [a], Tingxi Liu [a] and Xing Huang [a]

[a] *College of Water Conservancy and Civil Engineering College, Inner Mongolia Agricultural University, Hohhot, 010018, China*
Email: 122570400@qq.com

Abstract: With the continuous development of the population and social economy, the spatial and temporal distribution of water resources in arid inland river basins is severely uneven, and there is a sharp contradiction between agricultural water use and ecological water use. Irrational development and utilization of water resources has led to many problems, such as drying lakes, shrinking oases, intensified desertification processes, drying rivers, and environmental deterioration in the downstream regions (Chen et al. 2011; Deng & Shi 2014).

The goal of this study is to propose an ecological stability-oriented model suitable for conjunctive allocation of surface water and groundwater in oases in arid inland river basins. This model is based on the large-scale system decomposition–coordination principle, the water balance principle and the water supply and demand forecasting model. It can improve the water-use efficiency of the midstream agricultural irrigation districts and conjunctively allocate the surface water and groundwater (groundwater level) at the same time to realize the ecological stability and restoration of the downstream oases.

This model was applied to the Heihe River Basin, an inland river basin in Northwest China. The results show that under the premise of increasing water-use efficiency, the amount of water allocated to agricultural use is steadily decreasing, and the water-demanding crops are transformed from food crops to cash crops with low water consumption and high yield. With the population increase and economic development, the amount of water allocated to domestic use continuously increases. The amount of water allocated to ecological use gradually increases, and the area of oases and the mean groundwater level are continuously improving. In general, the proportions of water allocated to the ecology and economy tend to balance, and the result of water allocation is conducive to the sustainable use of water resources in the basin.

This model can optimize the planting structure and industrial structure and regulates the ecological groundwater level to coordinate the contradiction between ecological water use and water use in agricultural irrigation districts and thus achieve ecological stability and sustainable use of water resources.

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Keywords: *Conjunctive allocation, ecological stability-oriented, groundwater, arid inland river basin, surface water*

Non-stationarity of summer precipitation and its linkage with vegetation dynamics over a typical steppe in Inner Mongolia

Yixuan Wang [a], Linmin Duan [a], Tingxi Liu [a], Yanyun Luo [a] and Dongfang Li [a]

[a] *College of Water Conservancy and Civil Engineering, Inner Mongolia Agricultural University, Hohhot, 010018, China*
Email: wjxlch@126.com

Abstract: The typical steppe in Inner Mongolia is an important component of the Eurasian steppes. It plays a dominant role in preventing desertification and against sandstorms, but highly sensitive and vulnerable to climate change. Summer precipitation is one of the most important meteorological factors controlling plant growth, primary production, and species diversity/composition particularly in semi-arid grasslands (Zhao et al. 2019; Huang et al. 2020). Creating better understandings of the associated physical mechanisms of vegetation growth to summer precipitation anomalies will immensely contribute to ecological conservation and environmental protection in the semiarid ecosystem.

Based on long-term observed precipitation data and remotely sensed Normalized Difference Vegetation Index (NDVI) images, the non-stationary probabilistic model was used in the following three aspects. (1) To detect the non-stationary behaviors of summer precipitation, a parametric distribution was assumed for summer precipitation, and the distribution parameters were modeled as linear and/or nonlinear functions of time t using polynomial functions; (2) to investigate the temporal trends in vegetation changes, the time series of summer NDVI was fitted by a distribution with its parameters described as polynomial functions of time; (3) to examine the response of vegetation growth to summer precipitation variabilities, summer precipitation was used as covariate to describe the evolution of the parameters in NDVI modeling by cubic spline smoothing functions.

Results indicated that time-dependent models exhibited good performance to reproduce the temporal variations of eco-hydrological variables. The non-stationarity of summer precipitation was prominently visible for the majority of sites during the period from 1957 to 2017, with the mean behavior described as a linear or nonlinear time-varying pattern. In general, the steppe has experienced a decreasing trend in summer precipitation, but whether the decline tends to maintain or weaken or strengthen depends on the spatial location of the site studied. Differences appeared in the changes of vegetation in summer from 1998 to 2017 in different sub-regions. Evidences for the presence of stationary evolution was found in most sub-regions in the middle part, together with a linear increase in the westernmost sub-regions while a non-linear decrease in the easternmost sub-regions. Covariate analyses further highlighted the role of precipitation variabilities in the modeling of the NDVI-related vegetation dynamics over the steppe. The potential relations of summer precipitation to vegetation growth were characterized as both linear and non-linear positive forms. In particular, precipitation extremes could be responsible for the occurrences of exceptional cases in vegetation condition. The fluctuations in summer precipitation have crucial significance for future predictions of vegetation succession.

Findings from this study would lead to additional insights to understanding the effect of climate change on grassland ecosystem processes. Future studies should consider other driving factors as covariates in the nonstationary modeling to better describe the changes in eco-hydrological processes. The in-depth understanding of physical mechanisms in these changes and their linkages with explanatory covariates would be useful to provide insights to the effects of environment changes.

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Keywords: *Non-stationary precipitation, vegetation dynamic, climate change, NDVI, typical steppe*

A review of spatio-temporal variations of vegetation pattern through using remote sensing

Zhang Yiran [a]

[a] *College of Water Conservancy and Civil Engineering, Inner Mongolia Agricultural University, Hohhot 010018, China*
Email: 534805685@qq.com

Abstract: Vegetation is the main component of global ecohydrological system. The spatio-temporal evolution of vegetation pattern is of great significance to the diversity of ecosystem, the maintenance of benign hydrological cycle and the sustainable development of resources and environment (Dragoni et al. 2011).

The spatio-temporal evolution of vegetation pattern is characterized by the dynamics of patch structure, community distribution and landscape region on the spatial scale, and the transition of fluctuation, succession and history on the time scale (Sun et al. 2016). The use of advanced scientific and technological means of remote sensing can further clarify the dynamic changes of vegetation pattern and its own succession mechanism in the process of ecohydrology.

This research combs and summarizes the current researches on the spatio-temporal evolution of vegetation pattern from the perspectives of single remote sensing data source, coupled multi-source remote sensing data source and multi-temporal remote sensing. This research also makes an indepth analysis of the problems of scale, coordination and fusion of multivariate information and collaborative interpretation of multivariable and multi-elements in the current researches. Many problems faced in the research process restrict the indepth progress of remote sensing technology in vegetation research to a great extent. Therefore, in the future, while perfecting and innovating the research methods and theories of vegetation pattern, we also need to further improve its accuracy and universality.

On the basis of current researches, it is put forward that the nested multi-scale and multi-element integrated observation experiment of spaceborne-airborne-ground-connected interaction should be carried out in the future to realize the collection, transmission, storage and preliminary analysis of related index or parameter data of regional vegetation ecological-soil environment system. Develop and improve the remote sensing model and scale transformation method for the interaction of spaceborne-airborne-ground information, and put forward the remote sensing model and algorithm of key vegetation ecological-soil environment parameters at different scales. The artificial intelligence method driven by big data is used to realize multivariate information fusion and data assimilation. Construct variable sets and data sets of independent and dependent variables of different spatio-temporal scales, and combine big data-artificial intelligence-cloud technology to form a systematic remote sensing model and technical method system for multi-factor collaborative interpretation.

It is expected to provide new ideas and methods for the study of dynamic changes of vegetation pattern in large areas and with high precision.

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Keywords: *Vegetation pattern, remote sensing, multi-source data, environmental ecological effect*

Application of fusion of multi-source data in estimating biomass of grassland in Xilin River basin

Yajun Zhou [a]

[a] College of Water Conservancy and Civil Engineering, Inner Mongolia Agricultural University, Hohhot 010018, China
Email: zhouyajun154@qq.com

Abstract: Accurate monitoring of grassland biomass at high spatial and temporal resolutions is important for the effective utilization of grasslands in ecological applications. However, current remote sensing data cannot simultaneously provide accurate monitoring of vegetation changes with fine temporal and spatial resolutions. We used a data-fusion approach, the Flexible Spatiotemporal Data Fusion (FSDAF) method (Zhu et al. 2016), to generate synthetic normalized difference vegetation index (NDVI) data from Moderate-Resolution Imaging Spectroradiometer (MODIS) and Landsat data sets. We developed a suitable AGB estimation model for the Xilin River Basin based on the support vector machine (SVM), using AGB observation data, NDVI fusion data and meteorological data.

We estimated the grassland AGB on the Xilin River Basin in 2017, analyzed its spatiotemporal changes, and further explored the response of AGB to the variation in environmental factors. The results indicated that the FSDAF model performed well in the data fusion, which have clear textural characteristics and the simulated values are relatively close to the observed values with $R^2 = 0.75$.

The SVM-AGB model we developed can not only ensure the accuracy of estimation (R^2= 0.78, RMSE = 15.43 g/m^2), but also produce higher spatial (30 m) and temporal resolution (8-d) biomass maps.

The grassland AGB decreased from the southeast to the northwest in this region, Meadow grassland had the highest average of 59.98 g/ m^2. Grassland biomass peaked at the end of July, reaching a maximum of 190 g/m^2 in the southeast region of the basin and a minimum of 37 g/m^2 in the northwest. There was a significant downward trend in biomass from the first to the third week of August.

In the whole study area, the grassland AGB showed significantly positive correlation with SWC, TN, temperature and precipitation. Desert grasslands had the highest correlation for precipitation and relative humidity, and the increase of moisture could greatly promote the growth and development of grasslands and increase the biomass of grasslands. The response of biomass to surface soil water content was the most sensitive, with the highest correlation between typical grassland and soil water content and the highest correlation between meadow grassland and total surface soil nitrogen (0.785) among the different grassland types. This study demonstrated that FSDAF model can help improve our understanding of the spatiotemporal dynamics of the grassland AGB and the effects of environmental factors.

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Keywords: *Xilin River basin, biomass, data fusion, FSDAF, Support vector machine (SVM)*

A Bayesian framework for rainfall estimation and uncertainty quantification using reanalysis data: A case study for the Sydney region using ERA5 climate data

Rajitha Athukorala [a b] , **Dilani Kaveendri** [a c], **Nandini Ramesh** [a c] , **Vincent Chin** [a c], **R. Willem Vervoort** [a b] **and Sally Cripps** [c d]

[a]*ARC Centre for Data Analytics for Resources and Environments*
[b]*School of Life and Environmental Sciences, The University of Sydney, New South Wales, Australia*
[c]*School of Aerospace, Mechanical and Mechatronic Engineering, The University of Sydney, New South Wales, Australia*
[d]*CSIRO Data61, Eveleigh, New South Wales, Australia*
Email: rajitha.athukorala@sydney.edu.au

Abstract: Rainfall prediction is a long-standing challenge with applications in many fields. The diverse nature of atmo-spheric processes that result in rainfall makes it challenging to predict the timing and amount of rainfall that occurs. Advances in the frontiers of meteorological physics, numerical modelling and remote sensing have contributed to the generation of various reanalysis datasets. While these datasets have shown promising appli-cations at the global scale, their relatively coarse resolution limits their applicability in regional scale studies. We propose that climate variables from reanalysis data at a coarse grid scale, which are known to be closely linked with the processes governing rainfall, can be used to estimate the distribution of local rainfall as predic-tor variables in a Bayesian framework while quantifying uncertainties. The key objectives in this study were to:(i) establish a methodology to identify the most significant climate variables from a reanalysis dataset that can be used as predictor variables as indicated by model evidence using a Bayesian model averaging approach for the estimation of rainfall for a particular location, (ii) accurately estimate the average rainfall received using the significant climate variables in a linear regression and quantify its uncertainty, and (iii) compute the predictive distribution of rainfall for a test year. The proposed method was then applied to the Sydney Observatory Hill station data as a test case using 11 climate variables from ERA5 and the Southern Oscillation Index. Bayesian Model Averaging (BMA) was used for the selection of variables and Bayesian linear regression was used to build the model. Thereafter, a Gibbs sampling scheme was used to draw samples for each parameter from the conditional posterior distributions. Finally, the rainfall distribution and the predictive densities were calculated for a test year (2010) using the data from 1980-2009. Posterior estimates generated from the Gibbs sampler were used to obtain marginal predictive densities for the best 3 models. The mean vertical integral of moisture divergence, the vertical velocity at 800 hPa, near-shore sea surface temperatures, the mean evaporation rate and the cloud cover at medium height were found to be the 5 most significant variables, which were in line with existing literature. The mean values of the marginalized predictive density results were approximately equal to the actual observed values, showing the predictive ability of the selected significant variables. The methodology we developed provides a generalized approach for estimating rainfall at a point location using any reanalysis dataset, starting from variable selection up to making predictions while quantifying uncertainty.

Keywords: *Rainfall, downscaling, Bayesian model averaging, uncertainty quantification*

Flood forecasting with convective-scale ensembles in New Zealand: value of lagging forecasts

C. Cattoën [a], **S. Moore** [b], **T. Carey-Smith** [b] **and M.-H. Ramos** [c]

[a] *National Institute of Water and Atmosphere (NIWA), Christchurch, New Zealand,* [b] *National Institute of Water and Atmosphere (NIWA), Wellington, New Zealand,* [c] *Université Paris-Saclay. INRAE, UR HYCAR, 1 Rue Pierre-Gilles de Gennes, 92160 Antony, France*
Email: Celine.cattoen-gilbert@niwa.co.nz

Abstract: Over the last 50 years, almost half of the natural hazards in New Zealand are related to floods with a total cost of NZ$1.8 billion. Accurate forecasts can help mitigate impact and improve preparedness, however, accurately forecasting convective and orographically enhanced precipitation for hydrometeorological ensemble prediction systems is challenging with New Zealand's complex topography and steep and fast responding river catchments. Globally, the design of river forecasting systems using convection-permitting ensembles is an active area of research, but a trade-off is often required between system configurations (model resolution, ensemble size, frequency of forecast issue times) and operational or computational constraints.

In this study, we aim to understand how various weather ensemble configurations impact flood forecasts in hydrometeorological chains by addressing the following questions: How much skill do hydrometeorological forecasts using convective-scale models have out to 5 days? How do ensemble strategies (size, resolution, frequency) impact forecast accuracy, reliability and uncertainty representation during flood events? Can a lagged ensemble strategy (combining older and most recent forecasts) add value to flood predictions? What is the most efficient and affordable operational flood ensemble system configuration in terms of both scientific and computational performance?

The Numerical Weather Prediction (NWP) model used in this study is a local implementation of the UK Met Office-developed Unified Model. The New Zealand Ensemble (NZENS) is configured with convection-permitting model physics with a 4.5km horizontal resolution and features up to 18 members, available twice a day. Flood forecasts were produced by coupling several ensemble NWP configurations with the semi-distributed hydrological New Zealand Water Model (NZWaM). We evaluate multiple ensemble strategies for flood forecasting over a 12-month period for a sample of 60 representative New Zealand catchments and assessments of ensemble forecast accuracy, bias and discrimination of rainfall and streamflow forecasts made when i) increasing the NWP ensemble size from 6-18 members from the same issue time, and ii) combining NWP ensemble forecasts from older issue times (a lagged super-ensemble).

For a previous pilot study with the Buller catchment, all ensemble strategies were under-dispersed which is a common problem with NWP convective ensembles. Increasing ensemble size improved reliability and event discrimination more than accuracy, however performance between 9 and 18 members from the same issue time were similar. Using a lagged super-ensemble improved event discrimination for high flows with a trade-off of forecast accuracy and bias deterioration after a certain lead time threshold related to precipitation performance and nested catchment size.

We will discuss how these results apply on a larger sample size of catchment with varying characteristics.

Keywords: *Floods, ensemble forecasts, convective-scale, lagged ensembles, operational configuration*

EXTENDED ABSTRACT ONLY

Power transformation of variables for post-processing precipitation forecasts: regionally versus locally optimized parameter values

Yiliang Du [a], Quan J. Wang [a], Wenyan Wu [a] and Qichun Yang [a]

[a] *Department of Infrastructure Engineering, The University of Melbourne, Parkville 3010, Australia*
Email: yiliangd@student.unimelb.edu.au

Abstract: Short-term precipitation forecasts are mainly derived from numerical weather prediction (NWP) models. Raw NWP forecasts typically require post-processing to improve their accuracy and reliability through statistical calibration. For post-processing precipitation forecasts, several well-known calibration models employ power transformation to normalize data and homogenize their variances. The most common practice is to use a pre-fixed transformation parameter value for both observed and forecast variables, such as square root, cube root and *n*th root (referred to as the pre-fixed one parameter value approach here). Another approach is to allow the parameter values to differ for the two variables and locally optimize them at a spatial point to ensure the best performance of a calibration model (referred to as the locally optimized two parameter value approach). However, when calibrating forecasts across many grid points in a region, there is a considerable advantage in keeping the transformation parameter values constant, to enable spatial consistency in the calibration model so that model information transfer from gauged to ungauged locations can be easily achieved. For this reason, a third approach is proposed here to regionally optimize the parameter values for the two variables (referred to as the regionally optimized two parameter value approach). A question then arises: how do the two traditional approaches and the newly proposed approach affect forecast calibration performance?

This question is answered in this research by evaluating the calibration performance of precipitation forecasts at 20 locations across different climate zones in Australia. A seasonally coherent calibration model is incorporated with three different transformation approaches separately to postprocess daily precipitation forecasts from NWP models. By comparing the evaluation metrics among three transformation approaches, the results show that the pre-fixed one parameter value approach lead to poor performance, manifested as having large bias, wider ensemble spread and lower skill scores. The regionally optimized two parameter value approach is almost as good as the locally optimized two parameter value approach, and has the additional advantage of spatial consistence for regional applications.

Therefore, we recommend the use of the regionally optimized two parameter value approach, because of its strong performance in forecast calibration and its advantage for regional applications. The approach may also be relevant to other applications that involve spatial analysis of multivariate datasets and data transformations.

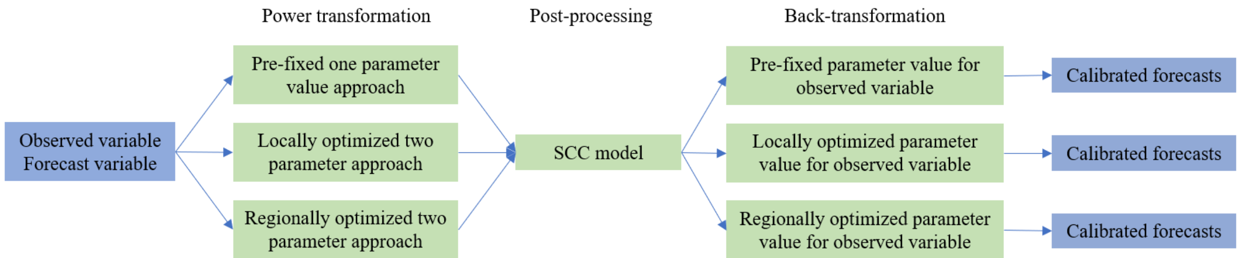

Figure 1. Processes of data transformations and forecast calibration

Keywords: *Data transformation, numerical weather prediction, post-processing, precipitation, forecast verification*

Using ensemble streamflow forecasts to improve seasonal determination outlooks and support irrigation decision making

Tristan D. J. Graham [a], Yating Tang [a], Quan J. Wang [a], Andrew Western [a], Wenyan Wu [a], Guy Ortlipp [b], Mark Bailey [b], Senlin Zhou [c], Kirsti Hakala [a] and Qichun Yang [a]

[a] *Department of Infrastructure Engineering, The University of Melbourne, Parkville, VIC. 3010, Australia.*
[b] *River Operations, Goulburn-Murray Water, Tatura, VIC. 3616, Australia.*
[c] *Water Forecasting Team, Bureau of Meteorology, Docklands, VIC. 3008, Australia.*
Email: Tristan.Graham@unimelb.edu.au

Abstract: Water is a vital natural resource. Its limited availability, high demand from human consumption and environmental needs, seasonal fluctuations and degradation of quality all necessitate its effective management. Across Australia, water managers are tasked with the delivery of appropriate quantities of water at the appropriate times, while ensuring the system is operated safely and sustainably. While individual water holders have entitlements for a given quantity of water, low availability for a given season may reduce the total proportion of that entitlement (determination) they are permitted to access. The common practice across the Murray-Darling Basin is for water managers to provide irrigators with information on seasonal determination outlooks for the coming season, updated monthly. Irrigators may then make their farm decisions, such as selection of crops, and activity in the water market, based on these outlooks. For example, Goulburn-Murray Water's (GMW's) current outlooks are based on storage levels and potential inflows. Several climate scenarios are published based on probabilities of exceedance estimated using historical records (climatology): extreme dry (99%), dry (90%), average (50%), or wet (10%). Two drawbacks of the current method are not using the best available information about future flows and yielding large uncertainty in the outlooks. This study aims to improve the accuracy and narrow the uncertainty of the seasonal determination using ensemble streamflow forecasts issued by the Bureau of Meteorology (BoM), allowing irrigators to plan with greater confidence for the coming irrigation season. The Goulburn system is used as a case study.

GMW's existing seasonal determination outlook tool was adapted and used with streamflow forecast ensembles for the three seasons 2017 to 2020. The BoM's ensemble monthly streamflow forecasts at the two key storage locations (Lake Eildon and Goulburn Weir) were used and compared with a benchmark forecast made using historical monthly inflow observations. Exceedance probabilities were then estimated from the ensemble outlooks. We evaluated the method by checking the width of uncertainty bands (sharpness), skill scores based on continuous ranked probability scores (CRPS), and reliability based on probability integral transform (PIT).

Our results indicate that the use of ensemble streamflow forecasts can generally improve outlook sharpness, reducing the width of uncertainty bands by up to 65% in the case study. This improvement reduced with increasing time between outlook issue and target months, with the greatest improvement observed in the three months for which streamflow forecasts were available. All CRPS skill scores were positive, indicating improvements over outlooks based on climatology alone. CRPS skill scores were highest for the target months with the shortest lead times, and for outlooks issued after the high flow months.

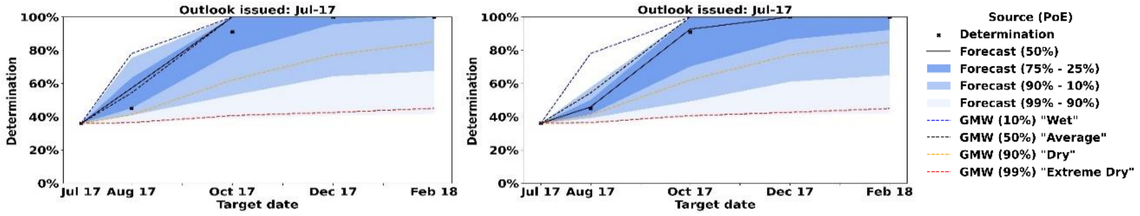

Figure 1. Seasonal determination outlooks issued Jul 2017 using climatology (left) and streamflow forecasts (right)

Keywords: *Seasonal determination outlook, ensemble, streamflow forecast*

Using short-term ensemble weather forecasts to evaluate irrigation decisions

Danlu Guo[a], **Quan J. Wang**[a], **Dongryeol Ryu**[a], **Qichun Yang**[a], **Peter Moller**[b] **and Andrew W. Western**[a]

[a] *Department of Infrastructure Engineering, The University of Melbourne, Parkville, VIC Australia*
[b] *Rubicon Water, Hawthorn East, VIC Australia*
Email: danlu.guo@unimelb.edu.au

Abstract: Irrigation is a major sector that consumes valuable and limited water resources. Effective irrigation scheduling can save water use while boosting water productivity. A key to achieving this is the accurate prediction of crop water use and soil water ahead of time. This study illustrates the application of ensemble weather forecasts to better incorporate uncertainties in soil water prediction, and thus assist irrigation decision-making.

In this study, we developed a framework for evaluating different irrigation scheduling decisions under uncertainties in future rainfall conditions. To achieve this, we incorporated the uncertainty in future rainfall by using ensemble short-term (9-day) rainfall forecasts, to estimate the performances of different irrigation decisions under uncertainty. A biophysical process-based crop model, APSIM (The Agricultural Production Systems sIMulator), was used to simulate root-zone soil water content for a study field in south-eastern Australia. For each irrigation decision, this modelling produced an ensemble of soil water content as well as irrigation runoff and drainage, which were used to quantify the probabilistic risks of over- and under-irrigation.

We identified the stress and wastage risks associated with different irrigation timings for each 9-day period within a full cropping season. We found that different periods of the season are dominated by contrasting patterns of risks, namely: 1) both stress and wastage risks; 2) wastage risk only; 3) stress risk only. Such risk information can assist the day-to-day irrigation decisions for farm managers, while allowing them to bring other management considerations into their decision making. Further, we also identified some critical conditions for which irrigation decisions should be carefully analysed and evaluated. High stress risks are often associated with low initial soil water level at the start of the irrigation cycle, while high wastage risks often arise for periods over which high rainfall amounts are forecasted.

Our future study will focus on extending the analysis framework to include other sources of uncertainties, such as evapotranspiration forecasts. Our ultimate goal is to build a comprehensive uncertainty framework to support on-farm irrigation decision-making.

Keywords: *Irrigation scheduling, irrigation timing, soil water modelling, crop water stress, uncertainty*

A comparative study on 10 and 30-year simulation of CMIP5 decadal hindcast precipitation at catchment level

M.M. Hossain[1, 2], **N. Garg**[2], **A.H.M. F. Anwar**[1], **M. Prakash**[2] **and M. Bari**[3]

[1]*School of Civil and Mechanical Engineering, Curtin University, GPO Box U1987, Perth, WA 6845, Australia*
[2]*Commonwealth Scientific and Industrial Research Organisation (CSIRO), Data61, Clayton Vic 3168, Australia*
[3]*Bureau of Meteorology, West Perth, WA 6872, Australia*

Abstract: Early prediction of precipitation has many positive benefits as it enables longer time for proper planning and decision making especially for the water managers, agricultural stakeholders, and policy and decision-makers. However, due to ongoing climate change along with the chaotic nature of precipitation, a too early prediction may lead to inefficient planning and decision making due to higher uncertainty and poor skills of the predicted data as the climate models are imperfect replicas that needs continuous improvement to predict future change. To investigate the difference between the short (a decade) and near-term (30 years) time simulation, this study aimed to compare the performance of 10 and 30-year simulation of CMIP5 decadal hindcast data of 0.05 degree spatial resolution at catchment level. For this, monthly hindcast precipitation of five general circulation models (GCMs); MIROC4h, MRI-CGCM3, MPI-ESM-LR, MIROC5 and CMCC-CM were downloaded from the CMIP5 data portal. Firstly the model data were cut for the Australian region and then the unit of the GCMs data was converted to the millimetre. In the next step, the GCMs data were spatially interpolated onto 0.05-degree spatial resolution using the second-order conservative method by Climate Data Operator (CDO) tool. Monthly observed gridded data of 0.05-degree spatial resolution were collected from the Australian Bureau of Meteorology (BoM). In the last step, both the observed and GCMs data were cut for the Brisbane River catchment in Queensland, Australia. Models' performances are assessed comparing with the corresponding observed values through four skill tests; mean bias, mean absolute error, anomaly correlation coefficient and index of agreement. The results show that, 30-year simulations have comparatively higher mean bias and lower skills than 10-year simulated data that seems relevant to ensemble numbers and the external forcing from increasing GHGs due longer simulation period.

Keywords: *Comparative, decadal, hindcast, precipitation, catchment*

EXTENDED ABSTRACT ONLY

Advanced wavelet-based variance transformation algorithms for ENSO forecasting over long lead times

Z. Jiang [a], A. Sharma [a] and F. Johnson [a]

[a] School of Civil and Environmental Engineering, University of New South Wales, Sydney 2052, Australia
Email: ze.jiang@unsw.edu.au

Abstract: Forecasting of hydrologic extremes across a range of timescales is critical for minimizing the socio-economic costs of these events. Consider, for instance, El Niño-Southern Oscillation (ENSO) is perhaps the strongest interannual signal in the global climate system with worldwide climatic, ecological, and societal impacts. Regression-based prediction is commonly adopted even in operational forecasting systems, often necessitating the use of distributional transformations to improve the model specification. One of the issues in such predictions, however, is the marked differences that distinguish the frequency spectrum of the hydrologic response from the predictor variables used. This raises the question of whether there exists an optimal predictor variable transformation that can mimic the frequency spectrum of the observed response.

In this study, we first discuss the need to transform predictor variables to improve hydrologic forecasts, and specifically focuses on the frequency domain of the variables involved. A number of alternatives using wavelet-based approaches are presented as a means of transforming the variance associated with different frequency bands in each predictor variable. The limitations and advantages of these transformations are summarized and demonstrated using different synthetic examples. More importantly, a stepwise variance transformation (SVT) framework is proposed that facilitates transformations of the residual error from a given predictor variable conditioned on existing predictor variables (Jiang, Sharma, & Johnson, 2021).

The SVT framework was used to obtain transformed predictor variables, and the dynamical linear model was applied to forecasting ENSO (Niño3.4 used in the study) over long lead times (up to 24 months). The data was partitioned into two subsets: training period 1960–93 and testing period 1994–2012. This approach was compared to a reference model without transformation (Std) as well as the original variance transform (VT) method presented in Jiang, Sharma, & Johnson (2020). The forecast skill of each model was evaluated by correlation and root mean square error (RMSE) across a range of lead times. We find that models with variance transformation led to the better characterized response (higher correlation and lower RMSE), and they deteriorated more slowly with increasing lead time than the reference model (i.e., Std). Additionally, comparing the VT and SVT approaches demonstrates the capability of the stepwise logic by transforming a particular predictor based on the residual information in the response given existing predictor variables that have already been selected for use in the model. The raw ENSO forecast results can be found at https://doi.org/10.6084/m9.figshare.16817572.v1.

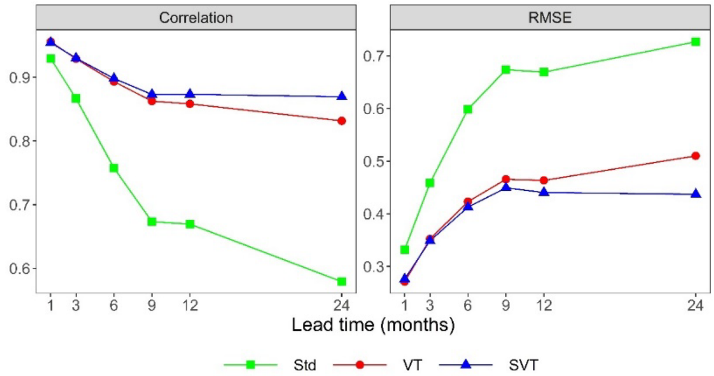

Figure 1. Forecast skills of three models by correlation and RMSE

The variance transformation approaches mentioned above have been implemented in an R library named WAvelet System Prediction (WASP), and more details can be found in Jiang, Rashid, et al. (2020). WASP is an open-source tool with sufficient help-files and can be downloaded from the Web site at http://www.hydrology.unsw.edu.au/software/WASP.

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Keywords: *Hydrologic forecasting, wavelets, transformations, regression*

From hydro-climate model to services: case study of the AWRA modelling system

Julien Lerat[a], **Andrew Frost, Jai Vaze**[a], **Elisabeth Vogel**[b], **Wendy Sharples**[b], **Ulrike Bende-Michl**[c], **Justin Hughes**[a] **and Shaun Kim**[a]

[a] *CSIRO, Land & Water, Canberra*
[b] *Bureau of Meteorology, Melbourne*
[c] *Bureau of Meteorology, Canberra*
Email: julien.lerat@csiro.au

Abstract: The delivery of hydro-climate science to stakeholders has recently seen a significant shift from traditional channels based on publications and one-off data packaging, to "on-demand" customised products that are frequently updated and where users select content interactively. This trend has recently accelerated due to increasing public interest and availability of large computing resources through cloud services. This talk presents the challenges and opportunities arising when standing up a hydro-climate service, starting from forging science partnerships to support model development, right through to user-centred design with a public-facing user-interface and data platform, via a case study: the Australian Water Resource Assessment (AWRA) modelling system.

The AWRA modelling system has been developed over the past 15 years as part of the Wirada alliance between CSIRO and the Bureau of Meteorology to deliver improved water balance estimates for the Australian continent. It initially included three components (AWRAL-L, AWRA-R and AWRA-G) focusing on landscape, river and groundwater systems, respectively. A first service was released in 2016 by the Bureau of Meteorology, soon to be upgraded with seasonal forecasts and hydro-climate projections as part of the Australian Water Outlook (AWO).

The talk will cover several key points related to this transition to "on-demand" combined hydrology and climate services, including the need to conduct user engagement and get a clear definition of end-user products, the challenges of coupling atmospheric and hydrological models, the need for transparent estimates of skill, confidence and uncertainty, the value of community modelling platforms and the importance of science partnerships.

Keywords: *Model integration, landscape models, rive routing models, water balance models, continental scale modelling*

A convolutional neural network-based post-processing method for precipitation forecasts

Wentao Li [a], **Baoxiang Pan**[b], **Jiangjiang Xia**[c] **and Qingyun Duan***[a]

[a]*State Key Laboratory of Hydrology–Water Resources and Hydraulic Engineering and College of Hydrology & Water Resources, Hohai University, Nanjing 210098, China*
[b]*Lawrence Livermore National Laboratory, Livermore, CA 94550, USA*
[c]*Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing 100029, China*
Email: wentaoli@hhu.edu.cn

Abstract: Raw forecasts from numerical weather prediction models suffer from systematic bias and cannot be directly used in applications such as hydrological forecasting. Statistical post-processing methods can be used to remove the bias and achieve reliable ensemble forecasts (Li et al., 2017). However, traditional post-processing methods only use local precipitation forecasts as the only predictor, which limits their ability to extract information from raw forecasts.

We develop a convolutional neural network (CNN)-based post-processing method for precipitation forecasts to fully make use of spatial information and atmospheric circulation forecasts. The post-processing model follows the EMOS framework, i.e., to predict the parameters of the distribution of the predictand by the post-processing model. As the distribution of precipitation amount is non-negative and skewed, we assume the predictand to follow the censored shifted Gamma (CSG) distribution, which has been successfully used in post-processing methods for precipitation forecasts (Scheuerer and Hamill, 2015). The structure of CNN generally follows the LeNet-type network. The output layer includes the three parameters of the CSG distribution, i.e., mean, standard deviation and shift parameters. The neural networks are fitted by minimization of an analytical expression of the mean continuous ranked probability score (CRPS) computed from the predicted CSG distribution and the true observations. The forecast dataset is a 20-year hindcast dataset named "ENS4ML" from ECMWF (ECMWF, 2020), which includes multiple meteorological variables such as total precipitation (TP), convective precipitation (CP), total column water (TCW), and geopotential height at 850/500/200 hPa pressure levels. The observation dataset is the 0.25°×0.25° gridded precipitation analysis developed by the China Meteorological Administration.

We compare the proposed model with a simplified version of the Bayesian joint probability (BJP; Robertson et al., 2013) model and an artificial neural network (ANN)-based model by 5-fold cross-validation during summer in Huaihe River basin in China. The results show that CNN-based post-processing model performs better than traditional methods in forecast accuracy, discrimination and reliability, especially for heavy rain at the lead time of 2 days. The CNN-based post-processing model outperforms the joint probability model in Brier skill score by 9% at the lead time of two days. Moreover, CNN-based models transcend the ANN-based model by using convolution layers to extract spatial information. The results illustrate the advantages of CNN-based post-processing models to extract spatial information and different meteorological variable information to improve precipitation forecast skill.

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Keywords: *Statistical post-processing, precipitation forecasts, hydrological ensemble forecasts*

Improving sub-seasonal streamflow forecasts across flow regimes

David McInerney[a], Mark Thyer[a], Dmitri Kavetski[a], Richard Laugesen[b], Fitsum Woldemeskel[c], Narendra Tuteja[b] and George Kuczera[d]

[a] School of Civil, Environmental and Mining Engineering, University of Adelaide, SA, Australia
[b] Bureau of Meteorology, Canberra, ACT, Australia
[c] Bureau of Meteorology, Melbourne, Victoria, Australia
[d] School of Engineering, University of Newcastle, Callaghan, NSW, Australia
Email: david.mcinerney@adelaide.edu.au

Abstract: Sub-seasonal streamflow forecasts are important for a range of water resource management applications, with a distinct practical interest in forecasts of high flows (e.g. for managing flood events) and low flows (e.g. for managing environmental flows). Despite this interest, differences in forecast performance for high and low flow events are not routinely investigated. Our study reveals that while forecasts evaluated over the full flow range can appear reliable, stratification into high/low flow ranges highlights significant under/over-estimation of forecast uncertainty, respectively.

This study introduces a flow-dependent (FD) non-parametric component into a post-processing model of hydrological forecasting errors, the Multi-Temporal Hydrological Residual Error (MuTHRE) model, yielding the MuTHRE-FD model. We use a case study with 11 catchments in the Murray Darling Basin, the GR4J rainfall-runoff model and post-processed rainfall forecasts from ACCESS-S, to compare the MuTHRE and MuTHRE-FD models. Through its improved treatment of flow-dependence, the MuTHRE-FD model achieves practically significant improvements over the original MuTHRE model in the reliability of forecasted cumulative volumes for: (i) high flows out to 7 days; (ii) low flows out to 2 days; and (iii) mid flows for majority of lead times. Example cumulative flow time series are provided in Figure 1. The new MUTHRE-FD model provides sub-seasonal forecasts with high quality performance for both high and low flows over a range of lead times. This improvement provides forecast users with increased confidence in using sub-seasonal forecasts across a wide range of applications.

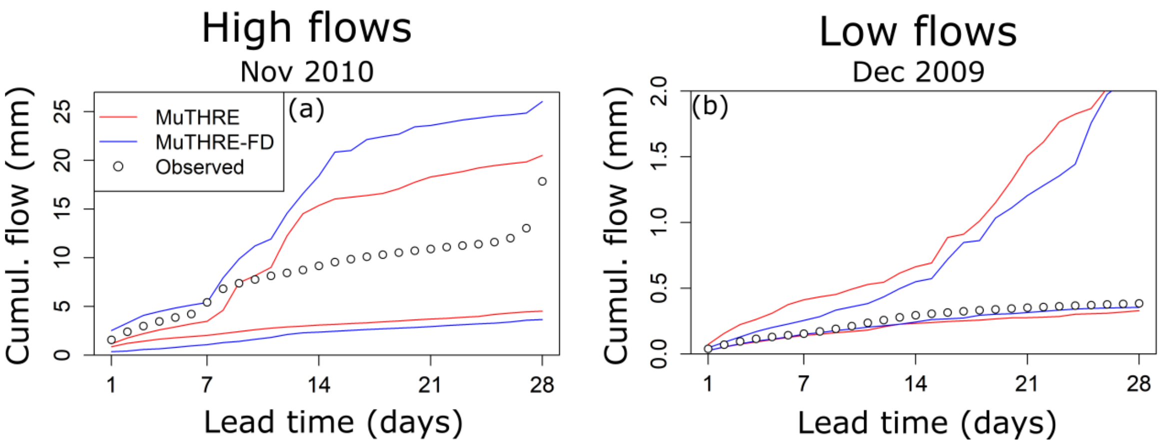

Figure 1. Example time series of predictive limits of cumulative volume forecasts out to 28 days for Hughes Creek (catchment ID 405228). Results are shown for forecasts issued on 1 November 2010, which is a high flow period (left side), and 1 December 2009, which is a low flow period (right side).

Keywords: *Subseasonal streamflow forecasting, high and low flows, non-parametric*

Assessing the impact of Earth Observation and in-situ data assimilation on seasonal hydrological predictions

Musuuza J.[a] **and Pechlivanidis I.**[a]

[a] *Swedish Meteorological and Hydrological Institute, Norrköping, Sweden*
Email: jude.musuuza@smhi.se

Abstract: Earth Observations (EO) have become popular in hydrology because they provide information in locations where direct measurements are either unavailable or prohibitively expensive to make. Recent scientific advances have enabled the assimilation of EO's into hydrological models to improve the estimation of initial states and fluxes which can further lead to improved forecasting of different variables. When assimilated, the data exert additional controls on the quality of the forecasts; it is hence important to apportion the effects according to model forcings and the assimilated data. Here, we investigate the hydrological response and seasonal predictions over the snow-melt driven Umeälven catchment in northern Sweden. The HYPE hydrological model is driven by two meteorological forcings: (i) a down-scaled GCM product based on the bias-adjusted ECMWF SEAS5 seasonal forecasts, and (ii) historical meteorological data based on the Ensemble Streamflow Prediction (ESP) technique. Six datasets are assimilated consisting of four EO products (fractional snow cover, snow water equivalent, and the actual and potential evapotranspiration) and two in-situ measurements (discharge and reservoir inflow). We finally assess the impacts of the meteorological forcing data and the assimilated data on the quality of streamflow and reservoir inflow seasonal forecasting skill for the period 2001-2015. The results show that all assimilations generally improve the skill but the improvement varies depending on the season and assimilated variable. The lead times until when the data assimilations influence the forecast quality are also different for different datasets and seasons; as an example, the impact from assimilating snow water equivalent persists for more than 20 weeks during the spring. We finally show that the assimilated datasets exert more control on the forecasting skill than the meteorological forcing data, highlighting the importance of initial hydrological conditions for this snow-dominated river system.

Keywords: *Earth observations, hydrology, forecasting, data assimilation*

EXTENDED ABSTRACT ONLY

Ensemble forecast-based dam release optimisation for controlled flooding

T.L. Ng [a], **D.E. Robertson** [a] **and J.C. Bennett** [a,b]

[a] *CSIRO Land & Water, Bayview Ave, Clayton, VIC 3168, Australia*
[b] *Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, TAS 7004, Australia*
Email: seline.ng@csiro.au

Abstract: In certain river systems, there is need for inducing medium size floods to support the ecology of riparian areas, by controlling the release from an upstream dam. At the same time, there is also need to maintain the risk of large floods below a threshold. In many places, the problem is complicated by tributary inflows which can be highly uncertain, and the lag time between the upstream dam release and downstream area for targeted flooding. To address this problem, we develop an optimisation program to yield the best release from a dam given a downstream flow target. The program considers medium-range ensemble forecasts of downstream tributary inflows and contains probabilistic constraints to limit the 'allowed risk' of large floods. An advantage of the program is that it provides a quantitative means of consolidating the complex mix of flow probabilities and lag times critical to the final problem outcome. In most places, this ability is still unavailable to river operators, who even now largely rely on qualitative means centred on human experience and intuition.

The program is mixed-integer in structure, which makes it challenging to solve within a reasonable runtime. The mixed-integer structure stems from the probabilistic constraints limiting the risk of large floods. Thus, to solve the optimisation program, we avoid conventional branch-and-bound methods. Instead, we take a simplified approach, where we separate the solving for the integer (binary) variables from the continuous ones. We test the optimisation program and our simplified approach to solving it on a case study of Hume Dam and Lake Mulwala in the southern Murray-Darling Basin. The results demonstrate their efficacy. From the results, we show the optimisation program capable of meeting the flow target when natural flows are low. And when natural flows are high, we find the ability of the program to meet the flow target to depend on the allowed risk of large floods; in general, we find that the larger the allowed risk, the better able the program to meet the flow target. However, the larger the allowed risk, the higher the probability of large floods, depending on the problem specification.

Keywords: *Dam release optimisation, reservoir optimisation, ensemble streamflow forecasting, chance-constrained optimisation, risk-based decision-making*

EXTENDED ABSTRACT ONLY

Concurrently generated inter-annual ensemble forecasts of surface and groundwater availability

David E. Robertson [a], **Guobin Fu** [b], **Olga Barron** [b], **Geoff Hodgson** [b] **and Andrew Schepen** [c]

[a] *CSIRO Land and Water, Clayton, Victoria, 3168, Australia*
[b] *CSIRO Land and Water, Floreat, WA 6014, Australia*
[b] *CSIRO Land and Water, Dutton Park, Queensland, 4102, Australia*
Email: david.robertson@csiro.au

Abstract: Surface water and groundwater are used conjunctively in many Australian irrigated agricultural systems and to meet urban water supply needs. Interannual differences in the availability, quality, and cost of water supply mean that the management choices need to balance these considerations. Ensemble forecasts of future water availability can inform such choices. However, where multiple sources of water are used, forecasts need to explicitly reflect the availability of both surface water and groundwater source and also consider the processes controlling their interactions. While forecasting methods have been developed to produce independent forecasts of surface water and groundwater availability, and operational services are available, there appears to be no methods for producing coupled forecasts that consider the surface water and groundwater interactions.

In this paper we describe an approach to generate coupled forecasts of surface water and groundwater availability. Our method extends the Forecast Guided Stochastic Scenarios (FoGSS) [*Bennett et al.*, 2016] approach to forecast groundwater level at specified locations, in addition to streamflow totals, to lead times of 12 months at monthly time steps. We adapt an existing conceptual hydrological model to improve streamflow predictions and, as a by-product, find that it can also be used to predict groundwater level. Independent error models are applied to streamflow and groundwater level to reduce bias, update predictions using recent observations and quantify residual uncertainty. Ensemble streamflow and groundwater forecasts are generated by forcing the hydrological and error models with ensemble rainfall forecasts generated by post-processing ECMWF System 5 outputs. The performance of rainfall, streamflow and groundwater level forecasts are assessed using measures of skill, bias and reliability for a case-study catchment in South-East Queensland, Australia. The results show that forecast skill is dependent on the forecast issue month and lead time. Streamflow forecast skill rarely persists beyond lead times of 3 months, after which forecasts resemble climatology. However, groundwater level forecasts display the significant skill to lead times of 12 months, with respect to both climatology and persistence references. We attribute the differences in skill characteristics between the streamflow and groundwater level forecasts to the groundwater system displaying responses to rainfall than the relatively fast-responding surface water hydrology. We conclude by describing opportunities to improve forecast performance and highlight some of the challenges that may be faced in the operational delivery of water resource forecasts in real-time.

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Keywords: *Ensemble forecasts, surface water, groundwater*

Inflow forecasting for hydro operations – the journey towards world's best practice

Kim Robinson [a], **James Bennett** [b], **Sarah Blundy** [d], **Prafulla Pokhrel** [c], **Andrew Schepen** [b], **Durga Lal Shrestha** [b] **and Mark Willis** [a]

[a] *Hydro Tasmania,* [b] *CSIRO Land and Water,* [c] *Entura – Hydro Tasmania,* [d] *WMAwater*
Email: Kim.Robinson@hydro.com.au

Abstract: Hydro Tasmania manages 30 hydro-electric power stations fed from 45 major lakes across Tasmania, 13,500GL of water is managed annually. As Australia's largest water manager, a major dam owner and a hydro-electric generator, understanding the hydrology in our catchments is crucial to Hydro Tasmania's business. To support our operations we need to understand hydrology across a full range of timescales - from what's happening in real-time to the impacts of climate change, through to how large a 1:10,000 year flood is likely to be.

In this paper we focus on the forecasting of short - long range inflows. These forecasts play an important role in optimising the operation of the system, assisting in minimising spill, maximizing revenue, and ensuring that flood and environmental risks are managed. These forecasts are generated by Hydro Tasmania's Dynamic Real-time Inflow Prediction (DRIP) system which produces forecasts at almost 70 locations across Tasmania, many of which are then used by reservoir routing models to predict levels at 35 lakes across the system.

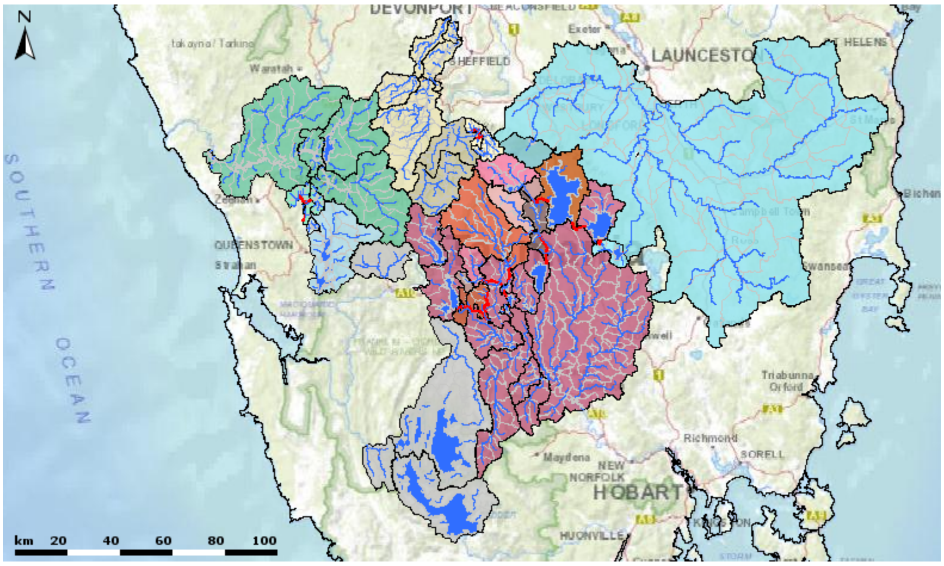

Figure 1. Model delineation across Hydro Tasmania's catchments.

The DRIP forecasting system generates 7-day deterministic inflow forecasts, these are generated every hour for 24 hours a day. Recent research has established that ensemble forecasts produce more accurate forecasts and have the added advantage of capturing the uncertainty. Hydro Tasmania is currently undertaking a major upgrade to the inflow forecasts, the conclusion of this project will see ensemble inflow forecasts implemented within the business. The upgraded system also aims to extend the forecast lead-time by utilizing long range climate forecasts in addition the medium range forecasts used to generate the medium range inflow series. Both the short- and long-range forecasting systems will use hybrid statistical-dynamical forecasting methods, making use of weather and climate predictions, statistical calibration, semi-distributed hydrological modelling and error modelling.

We are currently 6 months into the multi year project. An overview of the methods being implemented, the research components, the results to date, and the challenges with operationalising such a system will be presented.

Keywords: *Hydrologic modelling, ensemble forecasts, hydro power, inflow forecasting*

An improved trend-aware post-processing method for seasonal precipitation forecasts

Yawen Shao[a, b], Q. J. Wang[a], Andrew Schepen[c] and Dongryeol Ryu[a]

[a] Department of Infrastructure Engineering, The University of Melbourne, Parkville 3010, Australia, [b] School of Earth Sciences and ARC Centre of Excellence for Climate Extremes, The University of Melbourne, Parkville 3010, Australia, [c] CSIRO Land and Water, Dutton Park 4102, Australia
Email: yawens@student.unimelb.edu.au

Abstract: For managing the impacts of climate variability and change, seasonal climate forecasts are attracting more interests from climate-sensitive communities, such as water resource management, agriculture, and energy. Climate trends have been observed in recent decades across many parts of the world, but current global climate models (GCMs) for seasonal climate forecasting often fail to capture these trends. Previous research developed a trend-aware forecast post-processing method to address this issue, which built on the Bayesian joint probability (BJP) modelling approach. This method has shown robustness for resolving the trend disparity issue for seasonal temperature forecasts (Shao et al., 2021).

In this study, we aim to improve the trend-aware method for post-processing GCM seasonal precipitation forecasts. We modify the algorithm and introduce new evaluation tools to account for special characteristics of precipitation amounts, such as having a zero-lower bound, following a positively skewed distribution, and being more variable and uncertain than temperature variables in space and time. We apply this advanced version of the trend-aware method to calibrate Australian seasonal precipitation forecasts from the SEAS5 model, operated by the European Centre for Medium-Range Weather Forecasts (ECMWF). The trend-aware calibrated ensemble forecasts are compared with raw and BJP calibrated ensemble forecasts that do not have historical trend information embedded.

Our evaluation shows that the trend-aware calibrated forecasts properly capture observed trends and reproduce the magnitude of strong trends over the 36-year evaluation period (1981-2016), when raw and BJP calibrated forecasts fail to do so (Figure 1). Compared to the BJP model, the trend-aware calibration leads to marked skill improvement in the regions with statistically significant observed trends at 10% significance level. In most regions, trend-aware calibrated forecasts substantially outperform raw forecasts in terms of bias, skill, and reliability. Wider applications of this improved trend-aware post-processing method have the potential to boost user confidence in deploying seasonal precipitation forecasts for decision-making in a changing climate. Ongoing research will focus on adapting the trend-aware method for other hydrometeorological variables.

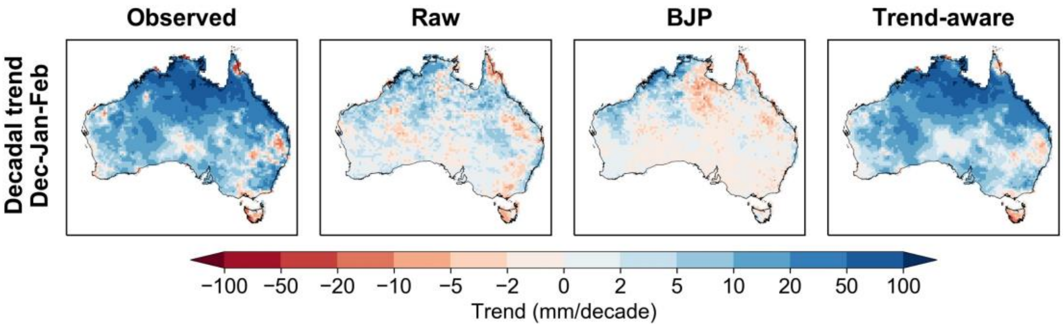

Figure 1. Decadal trend for observations, raw, BJP, and trend-aware calibrated forecast medians of Australian summer precipitation with 1-month lead time over 1981-2016

REFERENCE

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Keywords: *Seasonal climate forecasting, precipitation trend, forecast verification*

Advances in subseasonal streamflow forecasting: An overview

Mark Thyer [(a)], David McInerney [(a)], Dmitri Kavetski[(a)], Richard Laugesen[(b)], Fitsum Woldemeskel[(c)], Narendra Tuteja[(b)] and George Kuczera[(d)]

[a] School of Civil, Environmental and Mining Engineering, University of Adelaide, SA, Australia
[b] Bureau of Meteorology, Canberra, ACT, Australia
[c] Bureau of Meteorology, Melbourne, Victoria, Australia
[d] School of Engineering, University of Newcastle, Callaghan, NSW, Australia
Email: mark.thyer@adelaide.edu.au

Abstract: Sub-seasonal streamflow forecasts, with lead times up to 30 days, can provide valuable information for water management, including reservoir operation to meet environmental flow, irrigation demands, and managing flood protection storage. A key aim is to produce "seamless" probabilistic forecasts, with high quality performance across the full range of lead times (1-30 days) and time scales (daily to monthly). This paper provides an overview of advances towards subseasonal forecasting, by comparing the recently developed multi-temporal scale hydrological residual error (MuTHRE) model, one of the first approaches that provides seamless subseasonal forecasting, to an existing baseline residual error model and a non-seamless monthly streamflow post-processing (QPP) model. This comparison is in terms of model features and also through forecast evaluation on 11 catchments in the Murray-Darling Basin using multiple performance metrics, across a range of lead times, months and years, and at daily and monthly time scales. Compared to the baseline residual error model, the MuTHRE model is shown to provide improvements, in terms of reliability for short lead times (up to 10 days), in dry months, and dry years. Forecast performance also improved in terms of sharpness (Figure 1). Comparison against the non-seamless monthly QPP model showed MuTHRE provided similar reliability and sharpness for monthly forecasts stratified over months and years. This is a remarkable achievement, given the non-seamless monthly QPP models "sees" the monthly observed streamflow in calibration, whereas the MuTHRE model does not. This study highlights the benefits of modelling multiple temporal characteristics of hydrological errors, and demonstrates the power of the MuTHRE model for producing seamless sub-seasonal streamflow forecasts that have a wide range of practical benefits, as outlined.

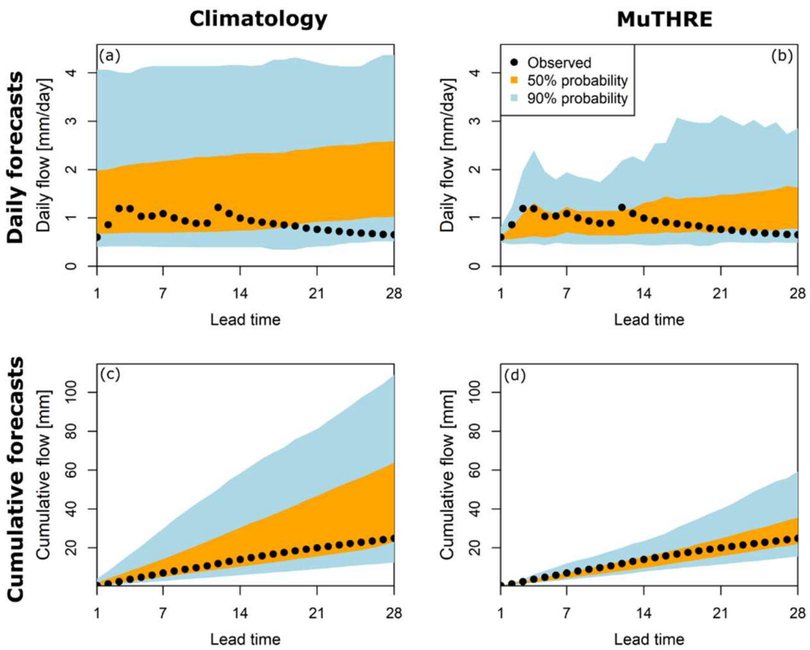

Figure 1. Streamflow forecasts in the Biggara catchment (401012) during August 2002. Climatology (left) is compared with the MuTHRE model (right). Both daily (top) and cumulative forecasts (bottom) are shown.

Keywords: *Subseasonal, streamflow forecasting, seamless, water resource management*

Estimation of road closure risks along the Bruce highway using the AWRA-L water balance model

E. Vogel [a], J. Lerat [a], L. A. Gericke [b], C. A. Russell [b], A. Preece [a], G. Stuart [a], R. Pipunic [a], Z. Khan [a] and C. Donnelly [a]

[a] *Bureau of Meteorology, Melbourne/Canberra/Brisbane, Australia*
[b] *Queensland Department of Transport and Main Roads, Brisbane, Queensland, Australia*
Email: elisabeth.vogel@bom.gov.au

Abstract: The Bureau of Meteorology, in collaboration with the Queensland Department of Transport and Main Roads, conducted a case study that aimed to evaluate the performance of nine-day runoff forecasts in predicting road flooding for selected river crossings along the Bruce Highway. The Bruce Highway is a major traffic carrier in Queensland and one of the most critical transport infrastructures in the state. Flooding in one of the close rivers along the highway can cause the road to be closed. Skilful forecasts of the risk of flooding several days ahead would provide an opportunity to prepare for the event and reduce any negative impacts for commuters on the highway. We developed and tested a method to relate simulated catchment runoff from the national AWRA-L water balance model with water levels at gauging stations close to major highways in Queensland. We found promising potential of predicting the risk of flooding in the next five days, as highlighted by high hit rates (average of 67.9% for moderate flood level at 15 stations) and low false alarm rates (average of 0.5%) for most stations and flood thresholds. This paper provides an overview of the evaluation results and outlines recommendations for future work.

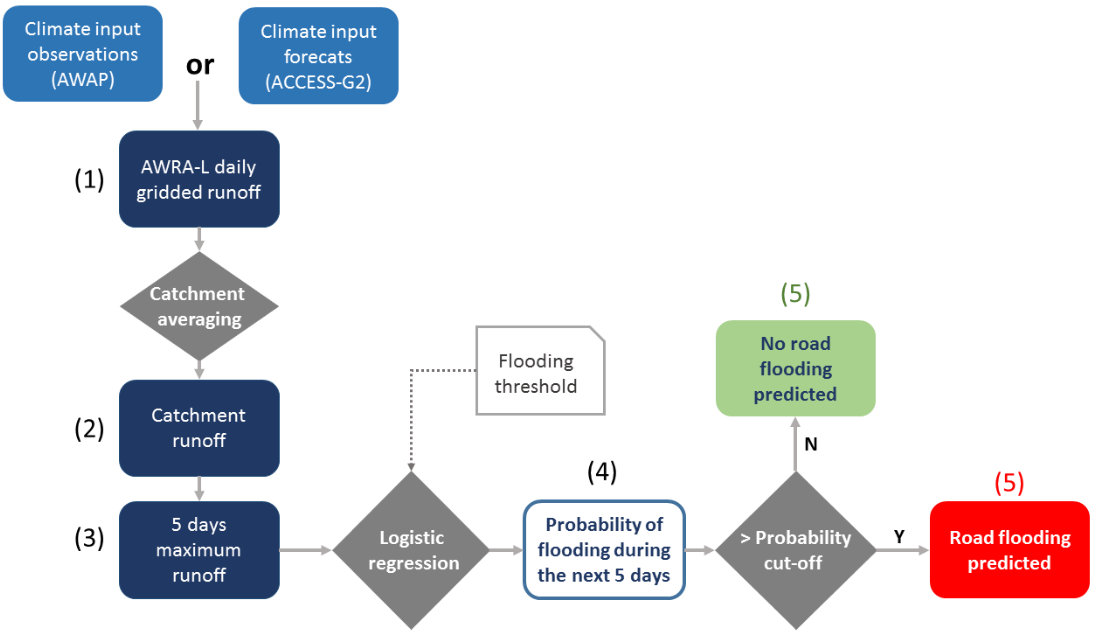

Figure 1. Flow diagram illustrating the generation of a road-flooding forecast.

Keywords: *Short-term forecasts, flooding risk, transport infrastructure*

Extending a joint probability modelling approach for post-processing ensemble precipitation forecasts from numerical weather prediction models

Pengcheng Zhao, **Quan J. Wang, Wenyan Wu and Qichun Yang**

Department of Infrastructure Engineering, The University of Melbourne, Parkville, Victoria 3010, Australia, Email: pengcheng@student.unimelb.edu.au

Abstract: Skillful and reliable ensemble precipitation forecasts are crucial for hydrological applications such as irrigation and flood forecasting. Precipitation forecasts that are routinely produced using numerical weather prediction models often exhibit bias and dispersion errors, thus require statistical post-processing. One prominent post-processing scheme is to establish a joint probability model by fitting a bivariate distribution of raw forecasts and corresponding observations. However, when applied to ensemble forecasts, current joint probability models can only incorporate ensemble mean as the predictor, and ensemble spread is not considered. This is a major disadvantage of joint probability models as ensemble spread can be informative for forecast uncertainty. Addressing this problem will increase users' confidence in using precipitation forecasts.

In this study, we propose a two-step calibration approach to integrate the additional forecast information included in the ensemble spread into joint probability models when post-processing precipitation forecasts. In the first step, we apply the seasonally coherent calibration (SCC) model as an example of joint probability models to calibrate the ensemble mean. As SCC for precipitation forecasts involves transformations for data normalization and special treatments of zero values, we establish SCC1, SCC2, and SCC3 by employing three different methods to estimate ensemble mean values (i.e., estimation before and after transformations, and with zero treatments, respectively). In the second step, we re-calibrate the ensemble forecasts produced in the first step to incorporate ensemble spread information from the raw forecasts. We select SCC3 from the first step to demonstrate the re-calibration (RC) method and we refer this two-step calibration model as SCC3-RC.

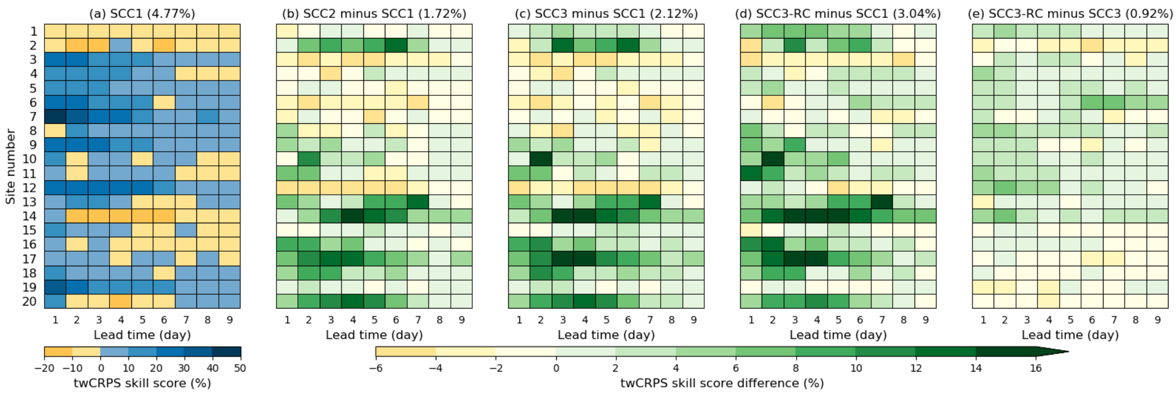

Figure 1. Cross-validation results of calibrated forecasts from SCC1, SCC2, SCC3, and SCC3-RC models in terms of skill score based on threshold-weighted continuous ranked probability score (twCRPS): (a) skill score of SCC1, and skill score difference between (b) SCC2 and SCC1, (c) SCC3 and SCC1, (d) SCC3-RC and SCC1, and (e) SCC3-RC and SCC3. The value in brackets of each subtitle represents the average value across the 20 sites and 9 lead times. A positive skill score indicates that calibrated forecasts are more skillful than the referenced climatology forecasts in forecasting heavy precipitation events.

We evaluate the performance of these models by applying them to ensemble precipitation forecasts from the Australian Bureau of Meteorology. For a comprehensive evaluation, we select 20 sites across a variety of climates in Australia. Results show that, on average, in the order of SCC1, SCC2, SCC3, and SCC3-RC, forecast skill tends to increase successively, indicating gradual improvements (Figure 1). The ways of calculating ensemble mean in joint probability models are thoroughly investigated, and the additional ensemble spread information extracted by the re-calibration is shown to bring considerable forecast skill increase into calibrated forecasts. Joint probability models are extended for post-processing ensemble precipitation forecasts using the proposed two-step calibration approach.

Keywords: *Numerical weather prediction, ensemble precipitation forecasts, statistical post-processing, joint probability model, ensemble spread*

Modelling snowpack dynamics across mountain ranges with SAR data

N. Bulovic [a], **N. McIntyre** [a,b], **F.M. Johnson** [c], **H. Lievens** [d], **T.E. Shaw** [e], **J. McPhee** [f] **and S. Gascoin** [g]

[a] Sustainable Minerals Institute, The University of Queensland, QLD 4072; [b] School of Civil Engineering, The University of Queensland, QLD 4072; [c] Water Research Centre, School of Civil and Environmental Engineering, University of New South Wales, NSW 2052; [d] Department of Earth and Environmental Sciences, KU Leuven, Heverlee, Belgium; [e] Swiss Federal Institute for Forest, Snow and Landscape Research (WSL), Birmensdorf, Switzerland; [f] Department of Civil Engineering, Universidad de Chile, Santiago, Chile; [g] CESBIO, CNES/CNRS/INRAE/IRD/UPS, Universite de Toulouse, Toulouse, France
Email: n.bulovic@uq.edu.au

Abstract: Seasonal mountain snowpacks act as regional "water towers" by storing snow over winter, which then melts during the warm, dry seasons providing freshwater to downstream communities and ecosystems. Mountain snowpacks are also vulnerable to climate change; yet, despite their importance and vulnerability, it is still a challenge to monitor and estimate snowpack over regional to global scales with ground-based observations, due to the large spatiotemporal variability and inaccessible terrain. Optical remote sensing of snow cover has partially bridged this gap, although it only provides information on the presence of snow (rather than volume) and is also affected by cloud cover. Other satellite remote sensing approaches, such as passive microwave, photogrammetry, and lidar have provided invaluable estimates of snow volume, but are either unsuitable for use over mountainous terrain, have high acquisition costs limiting application to individual catchments, or have coarse spatial and/or temporal resolutions.

For the first time, a recent study utilised C-band synthetic aperture radar (SAR) to estimate snowpack variability over mountain ranges of the northern hemisphere (Lievens et al. 2019). SAR is an active form of remote sensing where microwave energy is emitted from a sensor and the returning energy is measured as backscatter. Backscatter from snowy surfaces is a result of both diffuse and volume scattering, of which the latter is linked to snowpack volume. Snowpack variability was estimated through a simple change detection approach that quantifies the changes in backscatter (both VV and VH polarisation) between successive overpasses. The SAR data were acquired by Sentinel-1, the first global and freely available SAR satellite mission consisting of two satellites with a 6-day overpass frequency. Despite the exciting promise of this work, there still remain questions on whether this approach can be applied globally, under what conditions is it more or less suitable, and whether model accuracy can be improved by regionally-specific parameterization.

In this study, we apply the approach to the Andes mountains of Chile and Argentina – the largest snowpack in the southern hemisphere. The aims of this study are to firstly extend the initial modelling framework to a global scale by applying globally available remote sensing products. After which, the accuracy of the estimates are evaluated against in-situ data, distributed snow depth estimates from Pléiades, and are also compared to estimates from a land surface model. We identify the conditions under which the algorithm has better performance, such as maximum snowpack depth, base backscatter and regional climate. Last, we assess whether region-specific parameterizations can improve performance for an Andean application.

As Sentinel-1 data are freely available in near real time, have global coverage and the mission is to be extended, a major benefit of this work is the potential to provide near real time regional to global snowpack monitoring. Such data can be incorporated into streamflow forecasts seasonally and contribute to a climate data record in the longer term.

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Keywords: *Snow, mountains, Synthetic Aperture Radar, Sentinel-1*

An automatic system to estimate crop phenological dates with remote sensing: A case study in the southeast Australia

Zitian Gao [a], **Danlu Guo** [a], **Dongryeol Ryu** [a] **and Andrew W Western** [a]

[a] *Department of Infrastructure Engineering, The University of Melbourne, Parkville, VIC, 3010, Australia*
Email: zitiang@student.unimelb.edu.au

Abstract: Accurate crop phenological dates over large agricultural districts are important for managing agricultural activities and resources. Compared to farmer-reported calendars, satellite-based crop phenological dates can be spatially comprehensive and cost-effective. This study developed an integrated, fully automatic system that can generate crop phenological dates over a large region across decades. The system was developed in the R programming environment and linked to Google Earth Engine (GEE). We 1) used the R package "rgee" to send commands to GEE for satellite data acquisition and processing, and 2) applied state-of-the-art statistical algorithms to extract phenology metrics that represented key phenological dates from time-series data of vegetation indices. All analyses, including satellite data acquisition and pre-processing, calculation of vegetation indices and crop phenology analyses were written in a consolidated R script, making the analyses compactly packaged for efficient handling. The system was tested on three summer crops - corn (maize), cotton and rice over 113 fields in the Coleambally Irrigation Area (CIA) in southern New South Wales (NSW), Australia. We calculated the lengths of growth stages and start and end of the season (SOS and EOS) from phenology metrics for all fields and estimated their variabilities across the district. The satellite-derived crop phenological dates and lengths of growth stage were further compared with the equivalent dates used in FAO-56 and local crop growth guidelines.

The summer crop growing season in our study area starts from Oct-Dec and ends in Mar-May. The variability in the crop development stage length is relatively low compared to mid-season and late-season lengths. Cotton has the narrowest SOS and EOS time window, spanning roughly 1-1.5 months. Rice has more uncertain SOSs and EOSs that spread across 2-3 months. Differences are observed between satellite-derived phenological dates and the equivalent dates in guidelines, with the largest difference of 38 days found in the EOS for cotton. The phenological date detection system developed in this study is highly transferable to other periods or regions to benefit the local crop management.

Keywords: *Crop phenological dates, remote sensing, Google Earth Engine, rgee package*

How does total precipitable water link to precipitation extremes?

Seokhyeon Kim [a], **Ashish Sharma** [a], **Conrad Wasko** [b], **and Rory Nathan** [b]

[a] *School of Civil and Environmental Engineering, University of New South Wales, Sydney, NSW 2052, Australia.* [b] *Department of Infrastructure Engineering, The University of Melbourne, VIC 3010, Australia*
Email: seokhyeon.kim@unsw.edu.au

Abstract: In order to effectively minimize flood damage due to climate change, it is important to properly estimate the change in extreme precipitation (EP) due to temperature rise. A common way to predict EP is to use general circulation models (GCMs) that represent the physical processes of the Earth's climate system to simulate responses to temperature increases. Many existing GCM-based studies show that EP is projected to increase more in tropical regions than other regions, but GCMs have higher uncertainties in tropical regions due to limited modelling capacities. Another approach for EP projection is to utilize a covariate such as temperatures, expressed in sensitivity (%/K), commonly referred to as scaling. The scaling approach has been the basis of many studies examining tendencies in EP at various time scales with respect to surface temperature (SAT), dew point temperature (DPT), and total precipitation water (W). Although SAT has been primarily used in these scaling studies, the use of DPT with or without sub-daily data has also been proposed to obtain a clearer relationship with EP.

In the context of the latter (i.e., use of covariates), this study investigated the relationship between daily EP and corresponding total precipitable water (W) at a global scale by analysing 17-years of remotely sensed and reanalysis data from 2003 to 2019. The use of W for EP projection is advantageous in three respects. First, W is directly related to climate change because W shows a clear positive correlation with temperature. Second, the estimated W from satellites and models (i.e., reanalysis) agrees well with radiosonde-based observations. This means that rich and relatively accurate data from a variety of sources are available. Third, above all, W is a good descriptor for EP. We found that the W data consistently exhibit statistically significant upward trends over the study period. The upward trends prevail worldwide, especially in tropical land areas. We also found that W is generally positively correlated with Earth's surface (dew point) temperature, suggesting that the increased temperatures due to climate change may lead to an increase in W. The degree of W-EP involvement was quantified using the Concurrent Extremes Index (CEI). The CEI compares the cumulative distribution functions between EP and concurrent W where a value of unity is assumed when ranks of the EP series are identical to that of the coincident W series, and zero when no correspondence exists. Therefore, the higher the CEI, the higher the W-EP relevance. For EPs, which are defined as the five largest 1-day events per year on average, except for rainforest climates, higher CEIs are observed in the tropics. The relevance of W-EP is significantly reduced in non-tropical regions. In a sensitivity analysis for the W-EP, EPs become more relevant to W in the tropics as the number of days of precipitation accumulation and/or the average number of events per year increases. Our findings suggest that EP can be linked to W using the CEI-based W-EP relationship.

Keywords: *Extreme precipitation, total precipitable water, Concurrent Extremes Index (CEI), remote sensing, reanalysis*

High-resolution vegetation water content retrieval using Spaceborne C- and X-band Synthetic Aperture Radar

Dongryeol Ryu [a] and **Sun-Gu Lee**[b]

[a] *Department of Infrastructure Engineering, The University of Melbourne, Parkville, Victoria 3010, Australia*
[b] *Satellite Application Division, National Satellite Operation & Application Center, Korea Aerospace Research Institute, Daejeon, Republic of Korea*
Email: dryu.unimelb.edu.au

Abstract: High-resolution remote sensing of vegetation conditions, such as vegetation water content, biomass, and vigour, is important in monitoring agricultural production, risks of natural disaster (e.g., wildfire, floods, drought), wildlife habitats, and primary productivity of natural ecosystems. To date, optical remote sensing onboard satellites has been a primary method to monitor global coverage of vegetation conditions at high resolutions, however, availability of the optical imagery is sensitively influenced by the interference of clouds and aerosols and availability of solar radiation. Growing number of C- and X-band Synthetic Aperture Radar (SAR) satellites provides great opportunities to improve our current capabilities to monitor vegetation conditions at the spatial resolutions higher than 10 m with a significantly reduced influence of weather and solar radiation. In this work we demonstrate the efficacy of mapping the vegetation water content using two currently operational SAR satellites, X-band KOMPSAT-5 and C-band Sentinel-1, over dryland wheat fields of Victoria, Australia. Four different types of Radar Vegetation Indices (RVIs) based on cross-polarised imagery were used to establish Vegetation Water Content (VWC) model for wheat fields across the entire winter cropping period in 2019. The RVI values were first compared with the conventional Normalised Difference Water Index (NDWI) derived from the Sentinel-2 satellites. RVIs from both KOMPSAT-5 and Sentinel-1 presented a consistent linear association with NDWI across the whole growing season, however, Sentinel-1 derived RVI showed a large scatter for individual 'snapshot' level comparison. In comparison, KOMPSAT-5 presented more coherent comparison with Sentinel-1 NDWI, particularly for the RVIs that used VV and HV polarisations. The demonstrated efficacy of SAR-derived RVIs have important implications to all-weather monitoring of vegetation conditions at high spatial resolution and to spatially distributed hydrological and ecosystem modelling that requires gridded vegetation parameters at a range of spatial resolutions.

Keywords: *Remote sensing, vegetation water content, synthetic aperture radar*

Geostatistical merging of weather radar data with a sparse rain gauge network in Queensland

C. Sharp[a], **A. Schepen**[b], **S. Das**[a] **and Y. Everingham**[a]

[a] *James Cook University,* [b]*CSIRO*
Email: callum.sharp@my.jcu.edu.au

Abstract: Many parts of Australia, including much of Queensland and Northern Australia, tend to have sparse rain gauge coverage. To provide rainfall information across Australia, several gridded daily rainfall datasets such as those available through the Australian Water Availability Project and Scientific Information for Land Owners services have been developed. These daily grids are produced by interpolation of rain gauge data and therefore can provide unrealistic rainfall estimates in areas that have few rain gauges. To obtain rainfall data at a higher spatial resolution, weather radars and satellites can provide coverage over a large area although their measurements come with considerable uncertainty.

Various approaches have been developed to adjust radar and satellite data and statistically merge them with rain gauge measurements in interpolation schemes, the goal being to retain the information on the spatial distribution of rainfall provided by remote sensing while also taking advantage of the greater accuracy of the rain gauges, but many of these techniques have been applied primarily on shorter time scales of an hour or less.

This paper applies some existing methods for geostatistical merging of radar data with sparse rain gauge networks and evaluates the performance of the approaches using the Mt Stapylton radar in Brisbane and 15 surrounding rain gauges. Summer and winter data from 01/12/2013 to 28/02/2018 are considered. The radar data is corrected for mean field bias using quantile mapping and is used to develop the variogram models for use in Kriging. The performance of Kriging the gauge data using the radar variogram is compared with conditional merging and Kriging with radar values introduced as a drift variable. Leave-one-out cross-validation is used to evaluate the performance of the methods.

We find some disagreement between all radar-based approaches and the validation gauge measurements with typical daily root-mean-square errors being between 10mm and 20mm for all approaches. Some outliers with substantially higher RMSE are noted for some days in the unadjusted radar data as well as in the corrected and interpolated data. For winter data the bias-correction and interpolation steps increased the agreement between the radar data and the validation gauges, but this improvement was not observed in the summer data. In addition, due to the low number of gauges the performance of the interpolation is extremely sensitive to the rain gauge values, with certain combinations of rain gauge values and choice of validation gauge leading to extremely large cross-validation errors. The results indicate that while incorporating the radar data makes it possible to perform Kriging with few gauges on a single day's data, this is not an ideal approach for quantitative precipitation estimation and further steps should be taken to improve the radar-gauge correlation.

Keywords: *Weather radar, Kriging, rainfall, quantile mapping*

A bivariate filter for characterization of drying rates of satellite soil moisture drydowns

Jhilam Sinha [a], **Ashish Sharma** [a], **Lucy Marshall** [a] **and Seokhyeon Kim** [a]

[a] *Water Research Centre, School of Civil and Environmental Engineering, The University of New South Wales, Sydney, NSW, Australia.*
Email: j.sinha@unsw.edu.au

Abstract: Recent advances in satellite remote sensing have offered a viable alternative to conventional methods of determining soil moisture (SM) with increasing accuracy and a quasi-global coverage. However, verification regarding consistency between such remotely sensed and in-situ datasets due to different measurement depths and mismatch in spatial coverage, are often performed without any reference to the hydrologic process that modulates SM variability. A better understanding of satellite SM variability can be derived by accounting for hydrologic processes that govern SM depletion, commonly observed in in-situ datasets. Soil water retention-loss mechanism (depletion) is independent of any influx, primarily precipitation. This soil drying is dominated by evapotranspiration process, limited by availability of water in soil micropores and mesopores (drydown/recession), after undergoing rapid free drainage in soil macropores and a transitional phase of drying driven by atmospheric demand. Drying of soil impacts land energy and water balance and modifies hydrological extremes including floods, hence, are called hydrologic signatures. Consequently, accurate assessment of these drydown events is inevitable in minimizing uncertainty in hydrological investigations.

A filtering approach is introduced for minimising systematic deviations identified in drying rates of SM from Soil Moisture Active Passive (SMAP) L4 when compared to observed in-situ sensors. In total, 2089 pairs of drydown events (SMAP and in-situ) are selected from 525 in-situ stations globally. The soil drying rates are assessed using an exponential decay function that includes recession coefficient (k) and initial SM (first observation in drydown phase: θ_0). The filtering method aims to reduce discrepancies in recession coefficient and initial wetness jointly using a bivariate recursive procedure by minimising mean distance between SMAP and in-situ points in joint distribution plot of k and θ_0. This ensures an improved representation of the drying rate with sensible SM values (correction for wet biases) for the resulting SMAP series.

Considerable improvements are observed in resultant soil drying rates of SMAP drydowns with original SMAP and in-situ drydowns as displayed in the figure. Median SMAP drying rates before(after) filtering procedure for 5 days are 1.51(0.99), 1.42(1.03), 1.32(1.05), 1.26(1.05) and, 1.19(1.05) times higher than the in-situ drying rates. Higher sand content and drier climate accelerate the drying process by encouraging evapotranspiration process. However, no correction is implemented within the algorithm due to the absence of systematic biases between SMAP and in-situ drydowns in parameters (k, θ_0) with these covariates. Although the correction algorithm assumes spatial stationarity, it has shown improvements in regions with different sand fractions and dryness conditions providing a parsimonious alternative to better capture the dynamics of soil moisture loss. The present method can be implemented with other satellite derived SM products, suggestive of similar systematic errors, common in use for hydrological applications.

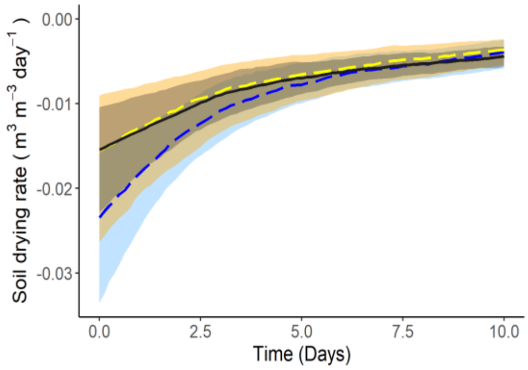

Figure 1. Drying rates of SMAP (blue), in-situ (yellow) and SMAP corrected (black) drydowns computed with corrected parameters (k, θ_0) in the validation. Median rates are represented by solid and dashed lines. 25th-75th percentile regions are shown by colour fills.

Keywords: *Bivariate recursive filter, drydown, remote sensing, SMAP, soil moisture*

EXTENDED ABSTRACT ONLY

Calibrating hydrologic models using surrogate streamflow in ungauged catchments

Hae Na Yoon[a], **Lucy Marshall**[a], **Ashish Sharma**[a] **and Seokhyeon Kim**[a]

[a] *School of Civil and Environmental Engineering, University of New South Wales, Sydney, New South Wales, Australia*
Email: h.yoon@student.unsw.edu.au

Abstract: We introduce a novel approach for hydrologic modelling in ungauged catchments using remotely sensed data. Due to widespread availability and global coverage, satellite data is an appealing option to fill the absence of streamflow data for hydrological model calibration in ungauged or poorly gauged basins. The satellite-derived calibration-measurement ratio (C/M ratio) is potentially useful because of the demonstrated correlation with observed streamflow. However, there are challenges in calibrating a hydrological model using the C/M ratio because it has a different magnitude to streamflow. Therefore, a new calibration approach is required to use the modelled surrogate streamflow instead of the raw C/M ratio in place of streamflow. A new Bayesian approach is developed here to identify parameters of surrogate streamflow in the absence of a time series of streamflow. This method calibrates the joint probability of the parameter set of a hydrologic model and a surrogate streamflow model. Specifically, the proposed likelihood includes auxiliary information, such as an estimated mean value of streamflow, to conjugate the information of streamflow volume and dynamics of the modelled flow. We assess our new approach for multiple Australian Hydrologic Stations with distinct attributes. The strength in the new approach is highlighted with high Nash-Sutcliffe Efficiency values (0.535 ~ 0.781), and quantification of the uncertainties in the new model calibration performed via Markov Chain Monte Carlo sampling. Specifically, the errors of the surrogate streamflow model and the hydrologic model are separately analysed, and the predictive intervals are assessed with the benchmark model derived from the in-situ streamflow. Overall, our work improves previous studies on the hydrological predictions using the C/M ratio. Furthermore, it enables the use of surrogate data known to have a high correlation to the true data, regardless of their dimensions.

Keywords: *Remotely sensed data, C/M ratio, Hydrologic Reference Station, Predictions in Ungauged Basins (PUB), Surrogate streamflow*

Amazon rainforest canopy responses during the 2019 fire season based on multiple satellite observations

Huixian Zhang [a], Daniel Fiifi Tawia Hagan [a] and Ricardo Dalagnol [b]

[a] School of Geographical Sciences, Nanjing University of Information Science and Technology, Nanjing 210044, China, [b] Earth Observation and Geoinformatics Division, National Institute for Space Research-INPE, São José dos Campos, SP 12227-010, Brazil
Email: h.x.zhang@nuist.edu.cn

Abstract: The Amazon rainforest is an important carbon sink in the earth, but confronted with a dual threat of climate extreme events and human induced fires. A better understanding of the vegetation dynamics caused by fires would help us to improve our regional and global assessments of carbon emissions, carbon cycle variability, and associated climate feedbacks.

The optical satellite observations with fine spatial resolution have been widely used to monitor the large-scale vegetation change. However, the higher concentration of clouds and aerosol over the Amazon region restricts its application in monitoring the forest responses to fire events. The passive microwave-based vegetation optical depth (VOD) is sensitive to vegetation water content and above-ground biomass comprising the leaf and woody parts. Importantly, it is minimally affected by atmospheric conditions due to its physical characteristics. VOD can reasonably capture vegetation changes over the tropical regions in response to large-scale extreme droughts and deforestation. However, its application in monitoring the vegetation variations associated with tropical forest fires is limited.

The Amazon rainforest suffered from one of the highest amount of fire activities during the fire season (July-October) in 2019, although the precipitation is close to the long-term average. This makes it an ideal test bed to examine the capacity of VOD to assess fire-driven canopy dynamics. A comparison of VOD and optical-based indices (e.g. NDVI, EVI, and NBR) is expected to reveal their consistency and difference in characterizing the canopy responses to fires.

Spatially, VOD were considerably below the average over the burned grid cells and close to the average over the non-burned ones. When it comes to the optical-based indices, below-average values were observed over both burned and non-burned grid cells, most likely due to the errors caused by the atmospheric conditions. When we focused on the temporal pattern of canopy changes over the burned grid cells, both VOD and the optical-based indices behaved similarly. Generally, with the increasing fire occurrences from July 2019, the magnitude of negative anomalies (i.e. below average) in vegetation indices became stronger and reached the strongest in September. Since October 2019, the negative anomalies in vegetation indices started to be smaller over the grid cells with fewer number of fire occurrences, which might be related to the canopy recovery. The recovery in the microwave-based VOD was slower than optical-based indices in October, which can be attributed to the fact that VOD is sensitive to both leaves and woody component of vegetation, whereas the optical-based indices are only sensitive to the leaves.

This study demonstrates the potential of (1) VOD for estimating vegetation change caused by fires in high biomass density forests, and (2) a synergistic application between the VOD and optical-based indices, which can provide a more comprehensive understanding of rainforest dynamics.

Keywords: *The Amazon, fire, vegetation optical depth, optical indices, canopy changes*

EXTENDED ABSTRACT ONLY

The impact of hydrological data assimilation on continental short-term and seasonal soil moisture forecasts

Katayoon Bahramian [a], **Ashkan Shokri** [a], **Elisabeth Vogel** [a], **Robert Pipunic** [a], **Ali Azarnivand** [a] **and Wendy Sharples** [a]

[a] *Bureau of Meteorology, Melbourne, Australia*
Email: katayoon.bahramian@bom.gov.au

Abstract: Landscape models have been developed to predict land surface processes such as terrestrial water cycle dynamics (e.g. of soil moisture and evapotranspiration) at various temporal and spatial scales. However, accurate prediction is challenging due to the uncertainty associated with model inputs, parametrization schemes, representation of processes, and initial conditions. Data assimilation (DA) has proved to be an effective approach for reducing uncertainty by combining the strengths of model predictions and observations through a weighted combination of their respective errors to generate optimal estimates. Assimilation of satellite soil moisture (SSM) data is a well demonstrated way of constraining model predictions by minimising errors in simulated hydrological states and fluxes. However, its efficacy has rarely been investigated for operational forecasting with large-scale (continental), high resolution (<10 km) landscape models.

The Australian Bureau of Meteorology (BoM) has developed an operational hydrological forecasting system using the gridded AWRA-L water balance model (Frost et al., 2018) forced with continental-scale numerical weather prediction model outputs (1-9 day) and seasonal climate forecasts (1-3 month). A computationally efficient Kalman Filter based DA scheme, using Triple Collocation (TC) error analysis (Tian et al., 2020), was implemented to assimilate top layer soil moisture data from the Soil Moisture Active Passive (SMAP) and The Advanced Scatterometer (ASCAT) on Metop satellites into the AWRA-L (v6) landscape water balance model. The impact of this DA scheme on top layer (s0: 0-0.1m depth) and root-zone layer (sm: 0-1m depth) is investigated in this study, where the soil moisture derived from: 1) historical soil moisture predictions (forced by historical observed climate data from AWAP) over 2015-2020, 2) short-term soil moisture ensemble hindcasts (forced by climate data from the BoM's numerical weather prediction model ACCESS-G2) over 2016-2019 and 3) seasonal soil moisture ensemble hindcasts (forced by climate data the BoM's climate forecasting system ACCESS-S1) over 2019-2020 are compared to observations and hindcasts.

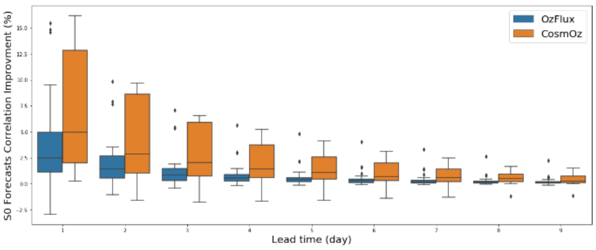

Figure 1. The correlation improvement (%) of data assimilated top layer soil moisture ensemble forecasts against CosmOz and OzFlux in-situ data at lead time 1-9 days (a).

Our results indicate that the DA approach improved the ensemble hindcasts by reducing model state errors relative to the reference datasets. We explored the spatial variation of improvements across Australian catchments and the temporal variation (persistency) of improvements as a result of this DA. Top layer soil moisture hindcasts were improved by 5% and 2.5% on average respectively across CosmOz and OzFlux sites for the first leadtime (1-day), while improvements gradually decreased at longer lead times (Fig.1). The improvements gained from DA could persist for approximately 4 to 9 days in top layer soil moisture estimates and 3 months in root-zone soil moisture hindcasts. These results demonstrate efficacy of this DA approach for the AWRA-L based forecasting framework. Accurate soil moisture forecasts play a vital role for informing early warning systems for floods and agricultural drought monitoring and water resources management studies.

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Keywords: *Continental landscape model, data assimilation, satellite data, soil moisture forecasting*

Enhancement of lightning strike forecasts using a machine learning approach

Gow, Daniel[a], **Julien Lerat**[b], **Rob Warren**[c] **and Ivor Blockley**[c]

[a] *Australian Bureau of Statistics, Canberra*
[b] *CSIRO, Land & Water, Canberra*
[c] *Bureau of Meteorology, Melbourne*
Email: julien.lerat@csiro.au

Abstract: This study represents a preliminary attempt to explore how a machine learning approach could be used to generate operational forecasting products in the Bureau of Meteorology. The objective of this paper is to compare feed-forward neural networks with the current operational system to generate forecasts on the likelihood of lightning strikes. The results presented here suggest that a network model based on off-the-shelf machine learning tools can rival or even surpass the performance of the current system when evaluated during a 90-day period and using a single performance metric (Brier skill score). The performance improvement was particularly noticeable when predicting lightning over the sea, where the current system consistently over-forecasts lightning. These results, although remaining a pilot study with no intention of operational deployment, are encouraging and show the potential for machine learning to support lightning strike forecast. The fact that off-the-shelf machine learning tools were used in this work indicate that the approach is cost effective with limited customised development needed, and potentially rapid deployment to operations.

Views expressed in this paper are those of the first author while on secondment to the Bureau of Meteorology and do not necessarily represent those of the Australian Bureau of Statistics. Where quoted or used, they should be attributed clearly to the authors.

Keywords: *Lightning strike forecast, deep learning, machine learning*

EXTENDED ABSTRACT ONLY

Continental-scale hydrological forecasts of soil moisture, runoff and evapotranspiration

E. Vogel [a], C. Pickett-Heaps [a], J. Lerat [b], S. Loh [a], A. Griffiths [a], V. C. Duong [a], K. Bahramian [a], Z. Khan [a], A. Shokri [a], A. Frost [a], D. Hudson [a], M. Griffiths [a], R. Pipunic [a], P. Sunter [a] and W. Sharples [a]

[a] *Bureau of Meteorology, Australia*
[b] *CSIRO Land and Water, Australia*
Email: elisabeth.vogel@bom.gov.au

Abstract: Seasonal hydrological forecasts are an important tool to increase Australia's resilience to withstand hydroclimatic variability and extremes (such as droughts and floods) by providing the opportunity to prepare for potentially harmful events and optimise decision-making in advance. The ability to forecast hydrological variables – such as soil moisture, evapotranspiration and runoff – across Australia several months ahead has many potential applications in different sectors, including agriculture (e.g. for optimising planting and harvesting dates, commodity forecasting or predictions of pasture growth), water management (e.g. in demand forecasting, environmental flows) and emergency management (e.g. for predicting bushfire and flood risk).

The Bureau of Meteorology has developed a continental-scale high-resolution seasonal ensemble forecasting system for soil moisture, evapotranspiration and runoff across Australia. The new system is a first of its kind in Australia and complements existing continental-scale climate forecasts of rainfall and temperature by translating climate outlooks into hydrological impacts and contextualising the Bureau's streamflow forecasts by providing the regional-scale context. The system uses a gridded water balance model, AWRA-L (http://www.bom.gov.au/water/landscape), forced with calibrated seasonal climate forecasts from the Bureau's ACCESS-S climate forecasting system, combined with a novel continental-scale hydrological data assimilation framework.

We comprehensively evaluated the accuracy and reliability of the hydrological ensemble forecast, using a range of verification metrics capturing deterministic and probabilistic skill and skill in predicting extremes (Vogel et al., 2021). In this presentation, we present the results of the performance assessment with a focus on use cases in the agricultural and water management sectors as well as for predicting hydrological extremes. We highlight potential applications of the forecasts, summarise strengths and limitations of the system and outline potential future research directions.

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Keywords: *Seasonal hydrological forecasts, ensemble forecasts, forecast verification, drought*

Enhancing short-term reference crop evapotranspiration forecasting through bias-correcting input variables and calibrating anomalies

Quan J. Wang [a], **Qichun Yang** [a] **and Kirsti Hakala** [a]

[a] *Department of Infrastructure Engineering, The University of Melbourne, Parkville 3010, Australia*
Email: quan.wang@unimelb.edu.au

Abstract: Weather forecasts (e.g., temperature, solar radiation, vapor pressure, and wind speed) produced by Numerical Weather Prediction (NWP) models have been used as inputs to produce ET_o forecasts. However, raw ET_o forecasts are often subject to systematic errors and need to be calibrated to improve forecast quality. In this study, we develop new calibration strategies based on the Seasonally Coherent Calibration (SCC) model to address two issues in NWP-based ET_o forecasting, i) error propagation from input variables to ET_o forecasts, and ii) insufficient representation of submmonthly trends of ET_o. Specifically, the non-linear interactions among the input variables in constructing ET_o could result in complex errors which could not be corrected through calibration. We apply the quantile-mapping method to correct bias in raw forecasts of individual input variables prior to constructing raw ET_o forecasts. This strategy effectively reduces error propagation from input variables to ET_o, and leads to more accurate and skillful calibrated forecasts, particularly at short lead times. In addition, ET_o often demonstrates increasing or decreasing trends at the submonthly scale. The SCC model parameterizes at a monthly resolution and does not capture the submonthly patterns of ET_o. We develop a new strategy to enhance ET_o forecast calibration by calibrating ET_o anomalies which are defined as departures from the climatological mean. This strategy successfully improves the correlation between calibrated forecasts and observations and increases forecast skills, particularly for forecasts at long lead times.

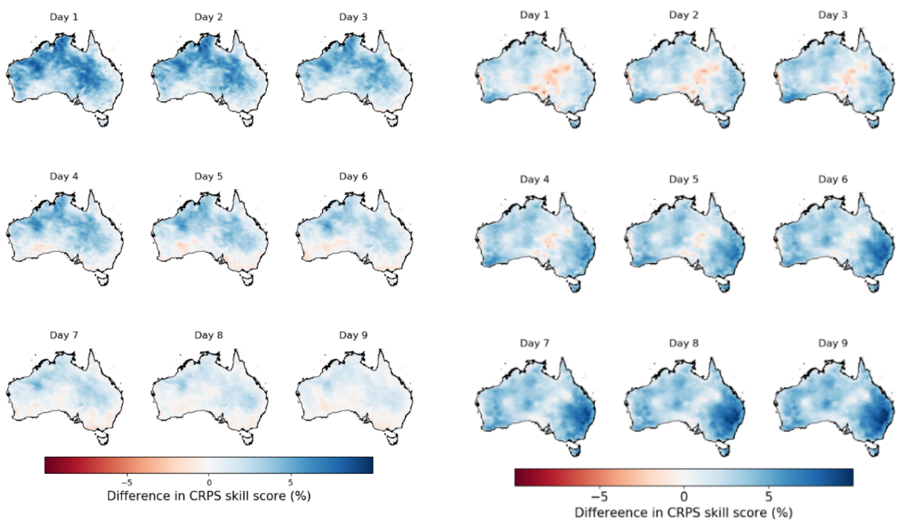

Figure 1. Improvements in CRPS skill score of calibrated ET_o forecasts through (three columns on the left) bias-correcting input variables and (three columns on the right) calibrating ET_o anomalies

REFERENCE

Yang, Q., Wang, Q., Hakala, K., Tang, Y., 2021. Bias-correcting input variables enhances forecasting of reference crop evapotranspiration. Hydrology and Earth System Sciences. 25. 4773-4788.

Keywords: *Numerical weather prediction, error propagation, seasonal patterns, climatological mean*

Seasonal reference crop evapotranspiration forecasting under a changing climate

Qichun Yang[a], **Quan J. Wang**[a], **Andrew W. Western**[a], **Wenyan Wu**[a], **Yanwen Shao**[a] **and Kirsti Hakala**[a]

[a] *Department of Infrastructure Engineering, The University of Melbourne, Parkville 3010, Australia*
Email: qichun.yang@unimelb.edu.au

Abstract: Seasonal ET_o forecasts are useful for water resource management and planning. Recently, climate forecasts from General Circulation Models (GCMs) have been increasingly used for seasonal ET_o forecasting. Due to errors in the predictions of future climate, raw ET_o forecasts constructed with GCM forecasts often contain systematic errors. As a result, statistical calibration models have been adopted to correct bias and dispersion errors in raw ET_o forecasts. Although these models are often effective in improving the forecast quality, time-dependent errors, resulting from GCM's misrepresentations of climate trends, have not been explicitly corrected in existing ET_o forecast calibrations. In recognition of this challenge, we reconstruct climate trends in ET_o forecasts through calibration and evaluate whether correcting the time-dependent errors would add extra skill to seasonal ET_o forecasts. Specifically, we calibrate raw seasonal ET_o forecasts constructed with climate forecasts from the European Centre for Medium-Range Weather Forecasts (ECMWF) SEAS5 model across Australia, using the recently developed Bayesian Joint Probability trend-aware (BJP-ti) model. We find significant inconsistencies between trends in raw forecasts and observations in both magnitudes and spatial patterns, particularly at long lead times. Calibration with the BJP-ti model successfully corrects misrepresented trends in raw forecasts and reconstructs observed trends in calibrated forecasts. Reconstructing trends through statistical calibration increases the correlation coefficient between calibrated forecasts and observations (r) by up to 0.25 and improves the continuous ranked probability score (CRPS) skill score by up to 15% in regions where climate trends are misrepresented by raw forecasts. Skillful ET_o forecasts produced in this study could be used for streamflow forecasting, modelling of soil moisture dynamics, and irrigation water management. This investigation confirms the necessity of reconstructing climate trends in GCM-based seasonal ET_o forecasts, and provides an effective tool for addressing this need. We anticipate that future GCM-based seasonal ET_o forecasting will benefit from correcting time-dependent errors through trend reconstruction.

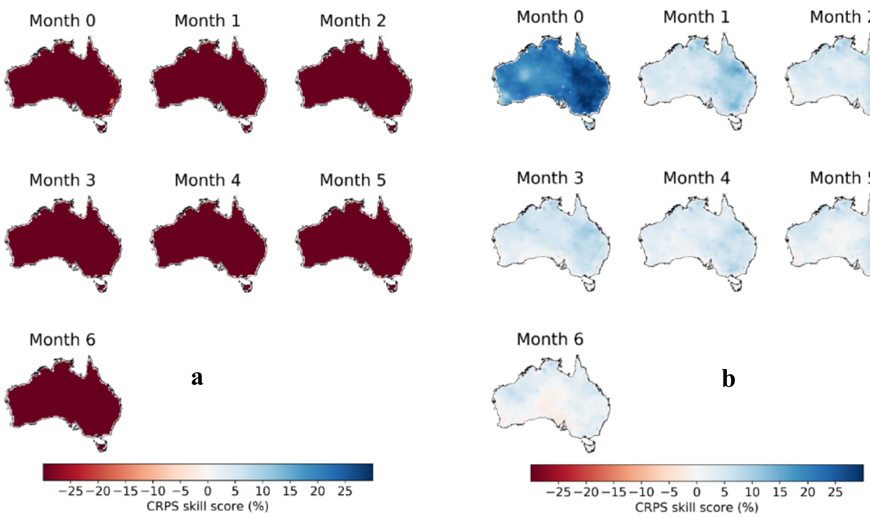

Figure 1. CRPS skill score in (a) raw and (b) calibrated ET_o forecasts during 1990-2019.

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Keywords: *GCM forecasts, climate trend, continental scale forecasting*

Comparison of connections between meteorological and hydrological droughts across the Murray-Darling Basin

Santosh K Aryal[1], **Hongxing Zheng**[1], **Jorge Peña-Arancibia**[1] **and Yongqiang Zhang**[2]

[1]CSIRO Land and Water, Canberra Australia, [2]Chinese Academy of Sciences, Beijing, China
Email: santosh.aryal@csiro.au

Abstract: Recurrent droughts are a common environmental feature across Australia. Large parts of eastern Australia including the Murray Darling Basin (MDB) have experienced major droughts e.g., the Millennium Drought (1996-2010) over the past 30 years. The Millennium Drought was unparalleled both in terms of its severity and duration whose effects were prominent in the southern regions of the MDB with winter-dominated rainfall. The northern regions of the MDB, which have mostly summer-dominated rainfall, were also affected by droughts of different magnitudes (BOM, 2015). We investigate meteorological (MD) and hydrological droughts (HD) using 48 years of precipitation and streamflow data from 1971 to compare the drought behaviours of catchments within the northern and southern basins of the MDB (Figure 1a). Hydro-meteorological data from the Australian Bureau of Meteorology's 132 hydrological reference stations (HRS) within the MDB were used. The northern and southern basins contain 37 and 95 HRS catchments with median catchment areas of 648 and 335 sq km respectively. Pearson correlations of HD and MD indices given by the standardised precipitation index (*SPI*) and the standardised streamflow index (*SSI*) respectively were analysed. These indices were calculated for each catchment using their respective best fit probability distribution functions for annual precipitation and streamflow data. The correlations of annual *SPI* with a drought surrogate, the annual zero flow days (*ZFD*s) or the 'cease-to-flow' days, were also investigated. The *ZFD* was calculated as the zero or near zero flows days based on the flow characteristics of a given catchment.

We found that MD and HD correlated well in catchments of both basins with comparable median correlation coefficients (r) (0.84 and 0.82 respectively) between *SPI* and *SSI* (Fig 1b). The spread of r, however, was higher with smaller low- and mid- quartile values for the southern basin indicating a prevalence of lower correspondence of meteorological and hydrological droughts in this basin. The meteorological drought indicator also negatively correlated to the *ZFD*, but the correlations were not as strong as those with the *SSI* (Fig 1c). The negative correlations indicate that as the wet periods, given by positive *SPI*s, increase the *ZFDs* decrease. The spatial distribution of r across the MDB shows a uniform spread of good correlations in both basins (Fig 1d). There were no lags between the annual MD and HD as well as between the MD and *ZFD*s in the basins indicating that both HD and *ZFD*s are responsive to MD at an annual time scale across the MDB.

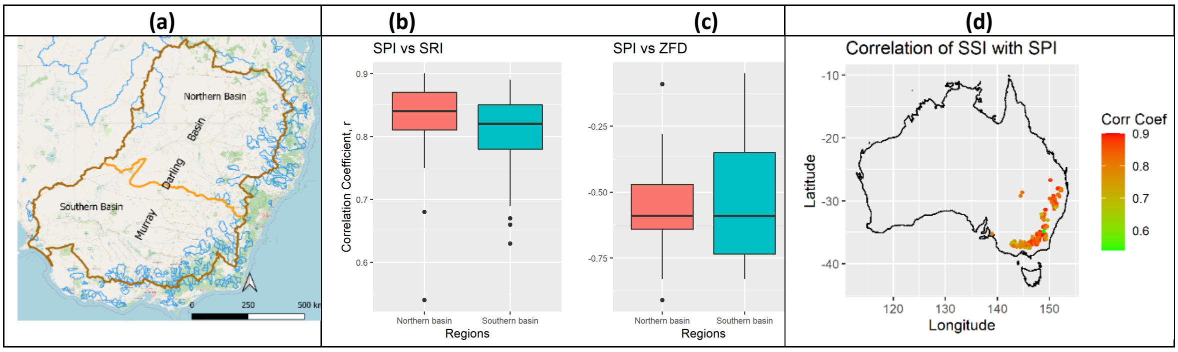

Figure 1. (a) The location of northern and southern basins of the MDB. Correlation between (b) SPI and SSI (c) SPI and ZFD in the two basins, and (d) spatial distribution of correlation coefficient within the MDB.

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Keywords: *Drought, Standardised precipitation index, Standardised streamflow index, MDB*

Performance evaluation and regional drought characteristics diagnosis based on a novel drought index

Muhammad Abrar Faiz [a] and Yongqiang Zhang* [a]

[a] Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China
Email: faiz@igsnrr.ac.cn, *zhangyq@igsnrr.ac.cn

Abstract: Drought severity is increasing due to the penetration of changing climate and lack of rainfall causing water deficit, which is resulted in reduction of agricultural production and a profound impact on the ecosystem. The study of dryness conditions using new techniques, models, or indices under changing climate could provide a scientific basis to mitigate the upcoming drought related risks and damages. Numerous researchers around the globe developed several drought indices to capture droughts. Each index has its pros and cons due to regional geographical limitations or climatic conditions. Thus, we proposed an index, namely composite drought index (CDI) which is based on precipitation, climatic water balance, and evapotranspiration (actual and potential). Proposed CDI is easy to calculate and do not need any distribution fittings (Fig. 1). The performance of the proposed CDI was assessed over different parts of China by taking more than 2400 gird points. We used scaled crop yield index (sCYI), remotely sensed soil moisture based standardized moisture index and evaluation with Palmer Drought Severity Index (PDSI). Pearson correlation and two statistical matrix probability of detection (POD) and false alarm ratio (FAR) are used to calculate the correlations with CDI and other indices and to detect mild to moderate drought events. The results demonstrated that CDI performs well in monitoring drought, as did PDSI. However, CDI performs better than PDSI when correlated with soil moisture and sCYI in the study area. Higher POD and less FAR of mild to extreme drought events using CDI make it relatively superior to PDSI but in the case of correlation with streamflow data, PDSI performs better than CDI. In conclusion, the proposed CDI may be used as a reference to detect drought conditions in other regions of the world that have similar environmental and climatic conditions as China.

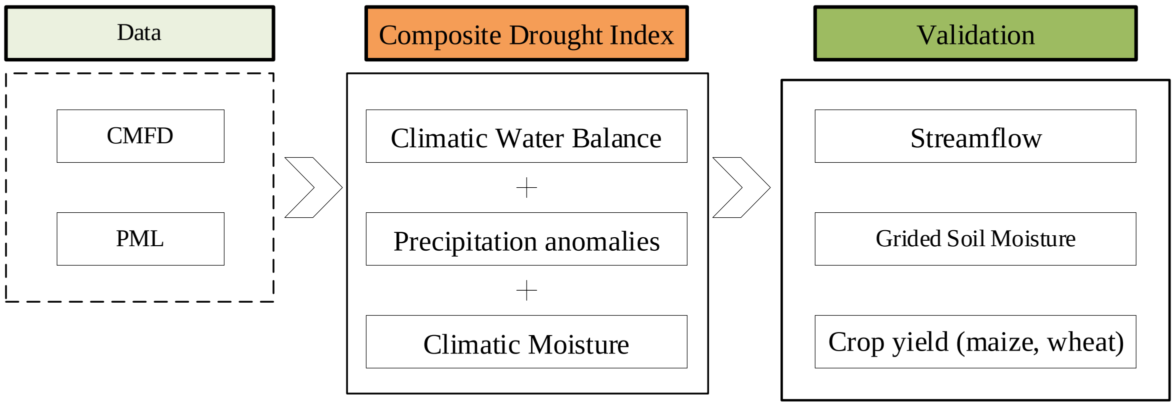

Figure 1. Proposed CDI framework using China meteorological forcing dataset (CMFD), Penman-Monteith-Leuning Evapotranspiration (PML) datasets based on climatic water balance, precipitation anomalies, and climatic moisture. Colum 3 is datasets that are used for validation of CDI.

Keywords: *Drought, SPI, Composite drought index PDSI, precipitation*

EXTENDED ABSTRACT ONLY

Reducing bias in streamflow projections generated using bias-corrected regional climate model rainfall

David E. Robertson [a], **Nick Potter** [b] **and Francis H. S. Chiew** [b]

[a] *CSIRO Land and Water, Clayton, Victoria, 3168, Australia*
[b] *CSIRO Land and Water, Canberra, ACT, 2601, Australia*
Email: nick.potter@csiro.au

Abstract: Regional climate models (RCMs) provide high resolution projections of future climate changes that can be used to inform assessments of future water availability and other hydrological investigations. However, it is well known that RCMs are unable to reproduce the statistics of rainfall observations, even when forced by reanalysis. Quantile-quantile mapping is commonly applied to reduce bias in RCM simulations of historical rainfall and projections of future rainfall. When applied to historical periods, quantile-quantile mapping is designed so that the bias-corrected RCM rainfall reproduces the distribution of observed rainfall exactly, or closely, depending in the assumptions of the algorithm. However, previous research has shown that a hydrological model forced by quantile-mapped daily rainfall produces biased streamflow simulations and biases are particularly evident for infrequently observed streamflow events. Investigation into the causes of these biases suggests that after quantile-quantile mapping the RCM-bias corrected daily rainfall still display bias in rainfall sequencing statistics, such as the probability of consecutive wet or dry days, leading to underestimation of multi-day rainfall totals that generate high streamflow events [*Charles et al.*, 2020; *Potter et al.*, 2020].

In this paper, we extend traditional quantile-quantile mapping to reduce bias in multi-day rainfall totals and rainfall sequencing statistics, by (i) concurrently mapping daily and multi-day rainfall accumulations, and (ii) adjusting the autocorrelation structure of the RCM outputs to better reflect that of the observations. We evaluate the sensitivity of rainfall and streamflow simulations to the quantile mapping extensions using dynamically downscaled reanalysis and historical GCM simulations for 11 catchments in southeast Australia. The results indicate that all quantile-quantile methods evaluated can effectively eliminate bias in monthly and annual rainfall totals. However, only methods that explicitly consider differences in the temporal dependence structures of RCM and observed rainfall are effective in reducing bias in rainfall sequencing statistics. Streamflow simulations generated by forcing a calibrated GR4J rainfall-runoff model with the improved bias-corrected rainfall display little overall bias. However, simulations of high streamflow values are underestimated when generated using quantile-quantile mapping methods that do not consider temporal dependence structures. We discuss opportunities and challenges for refining the extended quantile-quantile mapping methods and the implications for hydrological investigations of climate change.

Acknowledgements: This research is supported by CSIRO, Victorian Water and Climate Initiative (VicWaCI) and Murray Darling Water and Environmental Research Program (MD-WERP).

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Keywords: *Climate change, bias correction, hydrological projections*

A consistency assessment of CMIP3 and CMIP5 projections in Western Australia: Implications for long-term water availability planning

Margot Turner[a], Ulrike Bende-Michl[a], Artemis Kitsios[b], Pandora Hope[a], Alison Oke[a], Vjekoslav Matic[a] and Sri Srikanthan[a]

[a] *Bureau of Meteorology, Australia*
[b] *Department of Water and Environmental Regulation, Western Australia*
Email: Margot.Turner@bom.gov.au

Abstract: This paper presents a collaborative study between the Bureau and the Department of Water and Environmental Regulation to compare the Bureau's hydrologic projections and those being previously utilised within Western Australia that were based on CIMP3 data. This study identifies knowledge gains in explaining long-term impact of climate change on water availability and reliability and how this compares to previous results. This provides stakeholders with clear key messages on the change signal trends for the integration of the projections into water modelling and planning.

The National Hydrological Projection (NHP) service developed by the Bureau of Meteorology provides insights into the impact of climate change on Australia's water availability. This service brings together the nationally consistent hydrological capability of the Bureau's operational hydrological AWRA-L model (Frost and Wright 2018), dynamical and statistical downscaling (CCAM) and statistical bias correction techniques (MRNBC, QME, ISIMIP2b), applied to selected CMIP5 global climate models (ACCESS1-0, CNRM-CM5, GFDL-ESM2M, MIROC5). The service provides an understanding of changes to key hydrological variables across Australia, including rainfall, soil moisture, evapotranspiration and runoff from now until the end of the century under two emission scenarios. This service is sought to be complementary to hydrological projections developed elsewhere.

To undertake this consistency assessment, we explored long-term and seasonal climate and water availability trends in four study regions of Western Australia. We compared regional climate change signal for annual and monthly rainfall, PET and temperature from both. CMIP3 and CMIP5 projections. Both datasets identified the influence of seasonal drivers and baseline periods on the projected futures in each region and provided the key insights that are needed for water planning. A comparison of monthly rainfall projected by CMIP3 and CMIP5 ensembles in the region identifies seasonal influences and the declince in rainfall in the cooler months. 10th and 90th percentiles of the Bureau's ensemble are compared with dry and wet conditions of ensembles used in the previous State based CMIP3 projections.

The trends identified in the regional and site-based comparions will be presented. One example, in South-West Western Australia, increasing temperature and PET, inconjunction with decreasing rainfall project a continuing drying trend in this region. Runoff and soil moisture are projected to decrease significantly between 2050 and 2085. The spread of the CMIP3 monthly projections is greater then CMIP5 monthly projections from May to October. There is minmal difference in monthly drier futures (10th percentile), in contrast to greater differences in monthly wet (90th percentile) futures projected by the two projection ensembles for both the 2050 and 2070 time-slices.These differnces are used to investigate further how the projected change signal of each ensemble will influence water availability modelling outcomes for a site-based comparison. This includes how the climatology of different baselines may alter previous planning decisions.

Given the diverse range of needs and types of information that support strategic management decisions, guidance on the application of the projections service needs to be tailored towards specific applications. Consistency assessments, such as the collaborative study presented here, can contribute to the demonstration of such specific applications. A consistency assessment will be a necessary part of every upgrade of climate projections information. It provides insights into how the new projected futures vary spatially and temporally and what that means for previous water planning decisions.

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Keywords: *National hydrological projections, hydro-climate, assessments, water planning*

Explaining rainfall runoff changes associated with the Millennium Drought

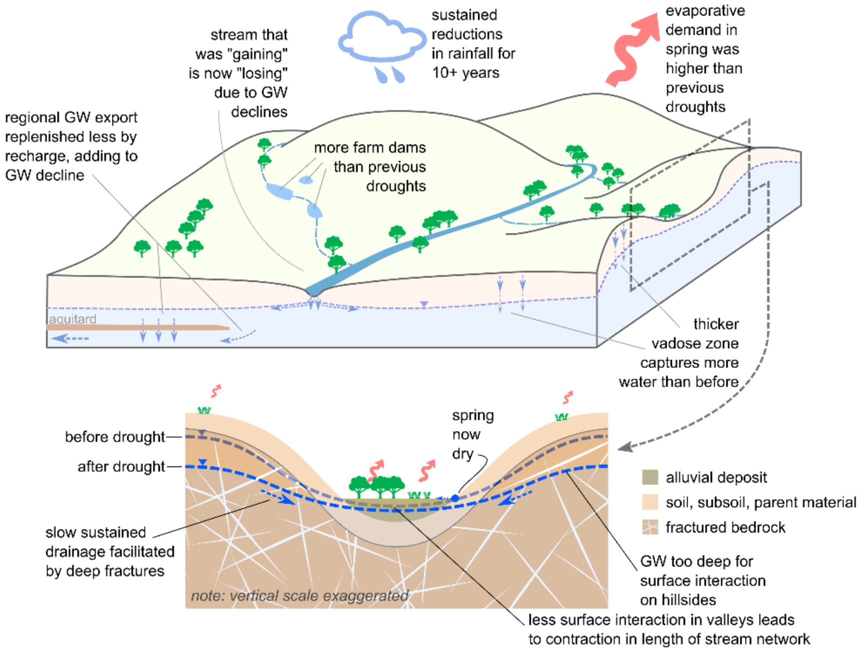
Keirnan Fowler[1], Murray Peel[1], Tim Peterson[2], Margarita Saft[1]… Rory Nathan[1]
Note: there are 33 co-authors of this submission – access the full list here.

[1]Dept.of Infrastructure Engineering, Univ. of Melbourne [2]Dept.of Civil Engineering, Monash Univ.
Email: fowler.k@unimelb.edu.au

Abstract: The Millennium Drought was a multi-year event notable for causing persistent shifts in the relationship between rainfall and runoff in many catchments in south-eastern Australia. Research to date has successfully characterised where and when shifts occurred, explored potential drivers, and noted changes in rainfall partitioning. However, a physical explanation for the changes in catchment behaviour is still lacking.

In response to these issues, we held a multi-disciplinary eWorkshop in late 2020 to discuss the hydrology of the Millennium Drought. Integrating perspectives from hydrogeology, ecohydrology, remote sensing, hydroclimatology, experimental hydrology and hydrological modelling, the workshop aimed to share and discuss "perceptual models" of flow response that could explain the Millennium Drought streamflow observations, considering both the spatial and temporal patterns of hydrological shifts. We considered a range of perceptual models of flow response, and then evaluated the models against available evidence. The models consider climatic forcing, vegetation, soil moisture dynamics, groundwater, and anthropogenic influence. Perceptual models were assessed both temporally (e.g. why was the Millennium Drought different to previous droughts?) and spatially (e.g. why did rainfall-runoff relationships shift in some catchments but not in others?).

The results (see Figure) point to the unprecedented length of the drought (10+ years) as the primary climatic driver, paired with interrelated groundwater processes: declines in groundwater storage, reduced recharge associated with vadose zone expansion/drying, and reduced connection between subsurface and surface water processes. An additional contributor is increased evaporative demand, and minor contributors may include farm dams, salinity recovery, and drainage via regional groundwater systems. The roles of deep-rooted vegetation, wildfire, rainfall patterns, and land use change, among others, were discounted on various grounds. Finally, we affirm the need to confirm these landscape-scale evaluations with local long-term field monitoring, particularly of subsurface dynamics, faced with the lack of such monitoring during the drought itself. We recommend continued investment in understanding of hydrological shifts, particularly given their relevance to water planning under climate variability and change.



Keywords: *Rainfall-runoff relationship, Millennium Drought, hydrological shift, catchment processes*

Attributions of climatic characteristics on nonstationary rainfall-streamflow relationship in southeast Australia

Guobin Fu[a], **Francis HS Chiew**[b], **Hongxing Zheng**[b], **David E Robertson**[c], **Nick J Potter**[b], **Jin Teng**[b], **David A Post**[b], **Stephen P Charles**[a] **and Lu Zhang**[b]

[a] *CSIRO Land and Water, Private Bag 5, Wembley, WA 6913, Australia*
[b] *CSIRO Land and Water, Canberra ACT 2601, Australia*
[c] *CSIRO Land and Water, Clayton VIC 3168, Australia*
Email: guobin.fu@csiro.au

Abstract: Nonstationary rainfall-streamflow relationships, due to human activity and changing climate, have been reported all over the world. Understanding potential changes in rainfall-streamflow relationship not only is a scientific challenge, but also has implications for hydrological modelling and management applications. For example, water resource planning and management that are based on the stationary rainfall-streamflow relationship may no longer be able to reliably estimate future water availability.

This study demonstrates the benefits of using a simple statistical analysis to investigate the attribution of climate characteristics to nonstationary rainfall-streamflow relationships in Victoria in southeast Australia. Rainfall and streamflow data from 65 Hydrologic Reference Station (HRS) (http://www.bom.gov.au/water/hrs/about.shtml) catchments are used to quantify the rainfall-streamflow relationship during (1997–2009), and prior to (1971–1996) and after (2010–2018) the Millennium Drought.

Annual streamflow is strongly correlated to annual rainfall, however the annual streamflow versus annual rainfall relationship can be very different in the different hydroclimate periods. The regression model against annual rainfall (AP) developed using the wet 1971–1996 period significantly overestimated the streamflow in the 1997–2009 Millennium Drought period. The model also fails to predict streamflow in the 2010–2018 post-drought period, where although the rainfall has recovered, the streamflow is still lower than the 1971–2018 mean.

The number of days with rainfall above 1 mm (RD) and the mean wet-spell length (MeWS) are found to be the two most "stable" variables that can best predict annual streamflow in the different hydroclimate periods. This is followed by the maximum and 99th percentile of 90-day accumulated total rainfall (D90Max and D90P99). The contributions of the MeWS to annual streamflow prediction should be emphasised. The combination of MeWS with many other climate variables significantly improved the streamflow prediction, particularly during the Millennium Drought.

The results differ in different regions. The climate variables can model the nonstationarity in the rainfall-streamflow relationship in the eastern part of Victoria, but none of the climate variables can model the nonstationarity in the drier western part of Victoria. The relative difference in the climate variables in the different periods can also help explain the nonstationary annual streamflow versus annual rainfall relationship.

The findings of this study can help identify key rainfall and climate characteristics to be considered in assessing the impact of climate change and climate variability on streamflow and water availability. They can potentially help develop hydrological models and hydroclimate relationships that can be more robustly extrapolated to estimate streamflow under a changing climate.

Detailed description of the methods and results can be found in Fu et al. (2021) and this study is funded by the Victorian Water and Climate Initiative.

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Keywords: *Rainfall-streamflow relationship, hydroclimate nonstationarity, climate change and variability, statistical analysis, Millennium Drought, Southeast Australia*

Mapping additional streamflow decline due to shifts in catchment response during the Millennium Drought

Margarita Saft[a], **Murray Peel**[a], **Phillip Jordan**[b], **David Shepherd**[b], **Geoffrey Steendam**[c], **Rebecca Lett**[c] **and Tim Peterson**[d]

[a] *Department of Infrastructure Engineering, University of Melbourne, Australia,* [b] *Hydrology and Risk Consulting (HARC)* [c] *Victorian Department of Environment, Land, Water and Planning* [d] *Department of Civil Engineering, Monash University, Australia*
Email: margarita.saft@unimelb.edu.au

Abstract: The Millennium drought has been challenging in many ways including scientifically. It is widely reported that runoff declines were larger than observed during previous droughts of similar magnitude but shorter duration. It has been shown that catchments shifted their hydrologic response to rainfall and this has been attributed to internal changes in catchment systems rather than meteorological factors. In other words, there was an emergent behaviour during the drought that was not experienced during the prior hydrologic record. This emergent behaviour, while widespread, affected different catchments differently. While some catchments exhibited a runoff decline that was two or more times larger than during previous dry years with similar rainfall decline, other catchments did not change their response and behaved similarly to other dry years. Given that the future climate in south-eastern Australia is expected to be drier, it would be useful to understand where the change in hydrologic response was more prominent and where the hydrologic response was more stable and resilient during the Millennium drought. While there is no guarantee that longer shifts in climate will not result in further changes in catchment response, it is still likely that the pattern of change will resemble the pattern encountered during the Millennium drought.

Here we characterise the additional runoff decline due to the shift in hydrologic behaviour and map it across Victoria on a 0.05° grid including ungauged locations. We use a large dataset of natural and semi-natural catchments to construct a predictive model for additional streamflow decline which is then applied to the state of Victoria. First, we separate runoff decline into "expected" streamflow decline (runoff decline in line with previous dry years with similar rainfall) and additional streamflow decline which we quantify across study catchments with long-term streamflow records. Then we use multi-model inference based on information theory to select a set of most informative predictors and construct a multivariate statistical model. This approach is particularly suitable for our dataset as we work with cross-correlated and potentially interacting predictors. The resulting model explains ~71% of the variance in the additional streamflow decline based on both catchment characteristics and meteorological anomalies of the drought. Once the suitable model is selected, we apply it across Victoria (except the arid north-west region) to create a map of additional streamflow decline. The fine resolution of the map allows the local spatial patterns, not present in earlier catchment-based studies, to be seen. The state-wide application provides estimates of the additional streamflow decline across the region and not tied to the study catchments for the first time.

The resulting map indicates which areas in Victoria are more resilient and which are less resilient to the shifts in hydrological response during prolonged periods of predominant dry conditions. While based on the Millennium drought, this map is likely to be applicable to future climatic shifts because the multivariate statistical modelling shows a strong relationship with catchment properties that will persist over time. While future shifts might be more widespread or severe, the Millennium drought gives us a useful new baseline of expected hydrologic response. More work is required to understand and quantitatively model the mechanisms of hydrologic shift, and while such models are not available this map can be used to gauge the potential of future hydrologic shifts under similar conditions.

Keywords: *Hydrological shift, multi-year drought, streamflow, information theory, catchment hydrology*

Observation based gridded annual runoff estimates over Victoria, Australia

H.A.C.G. Weligamage[a], **K.J.A. Fowler**[a], **T.J. Peterson**[b], **M. Saft**[a] **and M.C. Peel**[a]

[a] *Department of Infrastructure Engineering, University of Melbourne, Australia,*
[b] *Department of Civil Engineering, Monash University, Australia*
Email: hgardiyaweli@student.unimelb.edu.au

Abstract: In general, runoff generation is a highly variable process spatially. However, lack of spatially continuous runoff observations is a significant problem in surface hydrology due to gaps between gauged catchments and/or the need for within-catchment or ungauged catchment estimates. Recent efforts have produced programs for prediction in ungauged catchments, both in Australia (eg: Australian Water Resource Assessment – Landscape model *(AWRA-L)*) and internationally (eg: Prediction in Ungauged Basins *(PUB)*). While modelling approaches have many benefits (e.g. forecasting and projection), historic studies have the option of using observed data more directly. Adoption of geostatistical interpolation techniques potentially provides a more accurate method for generating spatially continuous runoff fields than modelling approaches. However, the use of geostatistical interpolation in hydrology is relatively uncommon because of the complex nature of hydrological connectivity. Here, we extend and apply *top-kriging* to spatially interpolate stream gauge data to produce gridded annual runoff across most of Victoria, Australia, from 1982-2012. Specifically, we extend the R-package *rtop* to allow kriging with external drift through the inclusion of spatial rainfall grids as a predictor. As expected, the resultant interpolated scheme provides a near exact match with observed values and acceptable performances in leave-one-out validation (R^2 of approximately 0.6 to 0.7 depending on year). The annual maps appropriately capture the variation in streamflow over time. Overall, this study illustrates that kriging can inform spatial runoff patterns and that the approach requires fewer inputs and less computational load than a complex numerical model. The methodology can be applied to any region with relatively minor adjustments. The dataset is open access in Zenodo repository at https://doi.org/10.5281/zenodo.5454798.

Keywords: *Gridded runoff, top-kriging, rtop package, prediction in ungauged basins*

Understanding shifts in evapotranspiration under a drying climate

H.A.C.G. Weligamage[a], K.J.A. Fowler[a], T.J. Peterson[b], M. Saft[a], D. Ryu[a] and M.C. Peel[a]

[a] *Department of Infrastructure Engineering, University of Melbourne, Australia,*
[b] *Department of Civil Engineering, Monash University, Australia*
Email: hgardiyaweli@student.unimelb.edu.au

Abstract: Globally, around 60 percent of terrestrial precipitation on average transforms into evapotranspiration. However, reliable estimation of actual evapotranspiration (AET) is challenging as it depends on multiple climatic and biophysical factors. Despite developments such as remotely sensed AET products, AET responses to prolonged drought is still poorly understood. Therefore, this study focuses on understanding long-term changes and variability of AET prior to and during the Millennium Drought in Victoria, Australia. We also investigate the capability of commonly used rainfall-runoff models to simulate AET under multiyear droughts. We examine four different water balance approaches (described in Figure 2). Surprisingly, the results indicate that the annual rates of pre-drought AET were largely maintained throughout the drought; ie. the rate was relatively constant with time (See Figure 2; example catchment 407214). This suggests that AET gets priority over streamflow following a drying shift in precipitation partitioning; resulting in a relatively constant AET under multiyear drought. In contrast, the rainfall-runoff models underestimated AET during the drought compared to both water balance approaches. These results acknowledge the need for model improvements to provide more realistic AET estimates under future drying climates and provide a new perspective on recent hydrological phenomena such as changing rainfall-runoff relationships in these regions. Furthermore, this sensitivity analysis was augmented and confirmed by a regional-scale water balance approach; we will discuss both approaches in our presentation.

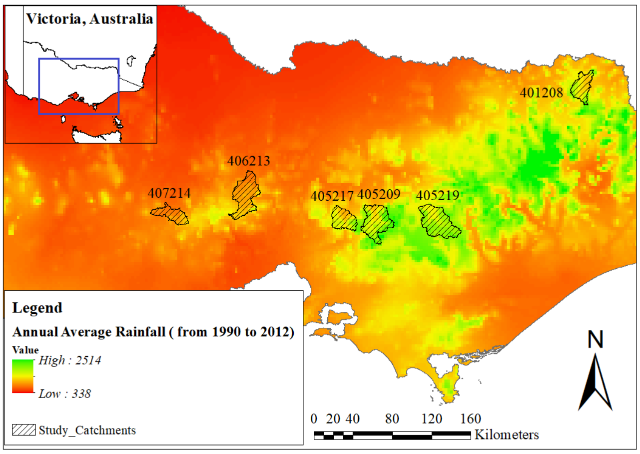

Figure 1. Selected six catchments in Victoria, Australia

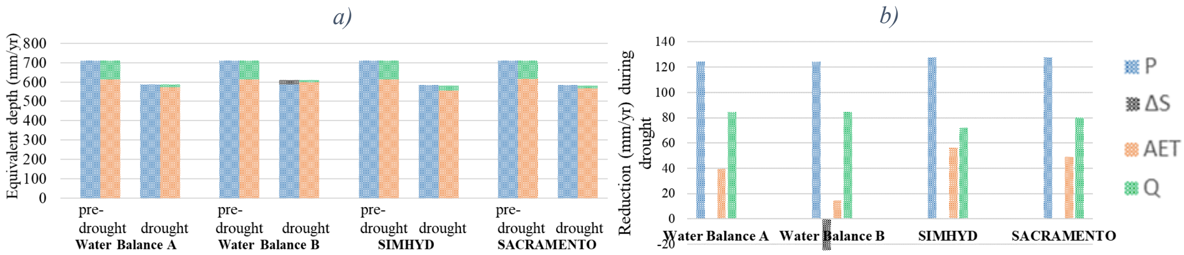

Figure 2. Comparison of water balances under different assumptions for an example catchment (407214). a) Pre-drought and drought water balance components for four different approaches. The simplest long-term water balance approach (P = ET +Q) is presented in Water Balance A. Water Balance B adopts the regional scale rate of change in GRACE estimates (ΔS) derived from Fowler et al. (2020) to represent the long-term decline in storage change in the catchment water balance approach during the Millennium Drought. For the purpose of sensitivity analysis, we make the simplifying assumption that the regional-scale GRACE measurements are applicable at catchment scale. The third and fourth water balances are based on simulations from SIMHYD and SACRAMENTO., b) Same data as panel a, except expressed as a reduction between pre-drought and drought periods. ΔS is negative for water balance B because the decline in water stored temporarily adds water into the water balance.

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Keywords: *Catchment water balance, evapotranspiration, change in storage, rainfall-runoff models*

Optimizing the multiple hydro-environmental benefits of green infrastructures using relative performance evaluation methods

T.F.M. Chui[1]

[1]*Department of Civil Engineering, The University of Hong Kong, Hong Kong SAR, China*
Email: maychui@hku.hk

Abstract: Green infrastructures (GIs) are decentralized small-scale urban drainage infrastructures that manage stormwater runoffs by utilizing natural drainage processes, such as interception, storage, infiltration, and evapotranspiration. GIs can simultaneously provide multiple hydro-environmental benefits, which include water quality improvement, flood risk reduction, and urban heat island effect mitigation. In GIs' design optimization, it is essential to collectively account for their various benefits when comparing multiple design alternatives. In current practices, these benefits are often quantified in terms of their monetary values, which can then be aggregated to represent the "overall" benefit. However, the processes of estimating the monetary values of intangible benefits can be tedious, and the preferences of the stakeholders towards different stormwater management targets cannot be reflected in the final assessment result. This study thus proposes an integrated performance assessment framework based on relative performance evaluation (RPE) methods for aggregating the multiple benefits of GIs, in which for each considered benefit each design alternative is assigned with a relative performance score by comparing its performance to that of all the other alternatives. The relative performance scores of each benefit are then normalized to values between 0 and 1, such that the best and worst alternatives receive a score of 1 and 0, respectively. The normalized scores of each benefit can be assigned with weights to reflect the preference of stakeholders. The weighted scores of different benefits can then be aggregated to represent the system-wide effectiveness of a design alternative. The proposed framework is applied to case studies in Hong Kong and New York City to identify the optimal GI design alternatives. The results show that in Hong Kong GIs should be implemented to treat stormwater runoffs from as large a catchment area as possible to maximize their benefits in water quality improvement, unless there are strong interests in managing the peak flows of moderate storms (for which small catchment areas are preferred). In New York City, green roofs and bioretention cells of 3%-5% of the area of green roofs are found to provide similar benefits in terms of stormwater management. In summary, the proposed RPE-based assessment framework provides a method to effectively aggregate the multiple benefits of the GIs with the consideration of the preference of stakeholders, which are useful for GIs' design optimization.

Keywords: *Stormwater management, green infrastructure, relative performance evaluation framework, design optimization*

Cooling Adelaide Summers by enhanced passive stormwater infiltration

H. Guan[a], **Z. Deng**[a], **R. Clay**[b], **X. Gleeson**[a], **Y. Zhou**[a], **and T. Johnson**[c, d, a]

[a] *National Centre for Groundwater Research and Training, & College of Science and Engineering, Flinders University, South Australia 5042, Australia*
[b] *School of Physical Sciences, University of Adelaide, South Australia 5005, Australia*
[c] *City of Mitcham, South Australia 5062, Australia*
[d] *UniSA STEM, University of South Australia, South Australia 5095, Australia*
Huade.Guan@flinders.edu.au

Abstract: With a warming climate, Adelaide is very likely to see more extreme hot days. Street trees can ameliorate its microclimate by canopy cooling from evapotranspiration, in addition to providing shade. This canopy cooling function depends on the availability of root zone moisture, which may diminish in the dry summer and autumn. In a project funded by City of Mitcham and Green Adelaide, we investigated the benefits of a street stormwater harvesting device, the TREENET inlets, on white cedar (*Melia azedarach*) canopy cooling in the summer and autumn in Adelaide. This study showed that TREENET inlets promote white cedar canopy cooling in summer. On average, TREENET inlets enhanced canopy cooling by 3.6 ^{o}C·hr/day for warm days, measured in and close to the tree canopy. The cooling enhancement occurred from midday to midnight, and peaked around 3 pm. The white cedar trees appeared to be sensitive to air temperature, vapour pressure deficit (VPD), and root zone water potential. The result indicates that the upper limits for canopy cooling are around 35 ^{o}C for air temperature, 3 kPa for VPD, and -0.45 MPa for root zone water potential. Beyond these thresholds, white cedar canopy cooling very likely diminishes. This result suggests that white cedar trees very likely lose their cooling power during heatwaves with daily maximum temperature above 35 ^{o}C.

Keywords: *Canopy cooling, stormwater harvesting, street trees, TREENET*

Web-based analyses of urban heat, vegetation and vulnerable populations to inform urban planning

Raymundo Marcos-Martinez[a], **Louise Ord**[b], **Sorada Tapsuwan**[a] **and Jacqui Meyers**[a]

[a] *CSIRO, Land and Water, Black Mountain, ACT 2601, Australia*
[b] *CSIRO, Data Analytics and Visualisation, IM&T, Eveleigh, NSW 2015*
Email: mar77v@csiro.au

Abstract: Higher urban temperatures can affect human health, air quality and energy use. Certain groups of people, such as those who are elderly, very young, or have certain mental or physical health conditions, can be more sensitive to high temperatures in their environment. People in low socioeconomic circumstances are also more vulnerable to extreme urban heat if high energy costs restrict their ability to cool their homes.

Urban heat can be mitigated in a number of ways; increasing the use of vegetation and water in the built environment, using 'cool' building materials, installing shade structures and reducing the amount of waste heat. These interventions provide cooling benefits through shade, evaporation, evapotranspiration, increasing reflectivity and emittance of materials and by channelling breezes. There is a relationship between tree cover and urban temperatures in cities; more trees mean cooler temperatures.

Identifying areas with high exposure to urban heat, little vegetation cover, particularly tree canopy cover, and high heat-related population vulnerability can assist with prioritising areas for urban heat mitigation actions. Many local governments have prepared, or are preparing, heat mitigation/adaptation strategies (e.g. Sydney, Melbourne, Darwin, Canberra). However, not all local governments have the resources to source the data sets needed to prepare a strategy, nor the software or technical skills to interpret the data and turn them into information that can support the development of the strategies. The type of questions that local governments ask in preparing heat mitigation/adaptation strategies are, 'where is it hot', 'what can be done about it', and 'where are the most vulnerable people so that heat mitigation or adaptation strategies can be prioritised'.

Following a risk assessment framework that accounts for hazard, vulnerability and exposure to extreme urban heat (Kaźmierczak and Cavan, 2011), we developed a web-based RShiny application that allows spatially detailed analysis of interactions between land surface temperature, urban vegetation and demographic information from mesh block to city scales in Darwin, Northern Territory, Australia. This tool can be used to identify which regions in a city have a high surface temperature, low vegetation cover, and high socioeconomic vulnerability. The tool allows non-technical users to define threshold levels for each parameter, e.g. regions with vegetation cover below 10% of the total area and heat vulnerability above the 80th percentile. The tool also estimates the distribution of vegetation within land-use types and planted and unplanted areas. This tool could be used by urban planners for rapid assessments of potential tree planting sites to mitigate urban heat island effects. The application also allows mapping and analysis of urban trees, and the framework will incorporate information from other urban sustainability indicators generated by the Darwin Living Lab (https://research.csiro.au/darwinlivinglab/).

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Keywords: *Urban forests, urban heat, sustainable cities, urban ecosystem services*

The cooling effect of vegetation evapotranspiration on urban heat island is more pronounced during nighttime and heat waves

GY Qiu, ZD Zou and CH Yan

School of Environment and Energy, Peking University Shenzhen Graduate School
Email: qiugy@pkusz.edu.cn

Abstract: Increasing urban heat island intensity (UHII) is one of the most serious human challenges in combination with global warming and it is expected to be mitigated by increased urban vegetation coverage (VC). However, the quantitative relationship between UHII and vegetation coverage is not yet well established. So far, existing research considers that the cooling effect of vegetation on UHII is only witnessed when VC is larger than a threshold value (usually 40%), while the cooling effect at night is assumed negligible. Here contrary to those previous assumptions, we show that there are significant negative relationships between UHII and VC during daytime, nighttime, and during heat waves, using an extensive two-year mobile transect observations (with more than 7000 repetitions) and five-year urban ET observation. We further show that the slope of the regression between UHII and VC is respectively -1.80, -2.62, and -3.67℃/100%VC for the entire day, nighttime, and heatwave periods, emphasizing that there is more cooling at night through VC. The cooling effect is also more evident during heat wave period as VC can decrease UHII by up to 2.62℃ and 3.67℃ during daytime and nighttime, respectively. This study provides new insights between the relationship of UHII and highlighting its potential to provide local mitigation strategy to combined global warming and UHII.

Keywords: *Urban heat island, heat waves, cooling effect, evapotranspiration*

Current and projected stocks of materials in Australian buildings and their environmental footprint

Natthanij Soonsawad[a], Raymundo Marcos-Martinez[a] and Heinz Schandl[a]

[a] *CSIRO, Land and Water, Black Mountain, ACT 2601, Australia*
Email: natthanij.soonsawad@csiro.au

Abstract: The construction industry is a major determinant of resource demand, greenhouse gas emissions, waste production, and pollution (Crawford et al., 2019). The construction and operation of buildings, and other built assets, account for the largest proportion of global energy use (35%) and global energy-related greenhouse gas emissions (38%) (United Nations Environment Programme, 2020). Infrastructure expansion in fast-growing cities could generate more than four times the CO_2e emissions used in the construction of existing infrastructure in developed countries (Bai et al., 2018). The materials and energy required to build, operate, and replace the infrastructure demanded by a growing population will increase environmental pressure and challenge climate change mitigation and adaptation efforts (United Nations Environment Programme, 2020).

In 2008, the total material footprint in Australia was about 740 million tonnes, i.e. around 35 tonnes per capita with, construction materials accounting for one-fourth of such amount (Wiedmann et al., 2015). In 2017, per capita domestic material consumption was around 38 tonnes, the third-highest within OECD countries (OECD, 2021). The use of building materials in Australia accounts for around one-third of total waste to landfill, and the carbon footprint of the construction sector represents 18% of the country's emissions (Yu et al., 2017). Energy and water use during building construction account for around 1% of the total national consumption (Treloar et al., 2004).

We estimated stocks of materials in residential, commercial and industrial buildings in 2016 from sub-suburb to country levels. We also estimate the GHG emissions, energy, and water footprint of building materials from extraction to delivery to construction sites (*cradle to gate)* and computed material intensity metrics (e.g. embodied building materials per capita) at different levels (e.g. state, country). Population projections and building service life assumptions were used to estimate material demand for new and replacement buildings from 2016 to 2060.

We estimate the material footprint of 8.8 million buildings at 3.8 billion tonnes with associated emissions of 1,804 million tonnes of CO_2e and consumption of 24,218 terajoules (TJ) of energy and 31.5 billion litres of water. Concrete accounts for 59% of the material footprint, followed by sand and stone, ceramics, and timber with 23%, 8%, and 4%, respectively. Most materials, 70.67%, are in residential buildings, while commercial and industrial buildings account for 24.67% and 4.66%, respectively. By 2060, the projected material demand for new buildings and replacing ageing buildings ranges from 4.3 to 7.5 billion tonnes for alternative population growth scenarios. The upper range of the demand signals a two-fold increase in building materials and associated environmental impacts by 2060. Considering this, if Australia does not change the way construction materials are produced and buildings are designed towards sustainable outcomes, the country will struggle to achieve its net-zero emissions target.

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Keywords: *Material footprint, spatially explicit analysis, circular economy, embodied GHG emissions*

Improving the Jarvis-type model with modified temperature and radiation functions for sap flow simulations

Hailong Wang[a,b,c], **Huade Guan**[d], **Na Liu**[d,e], **Chris Soulsby**[f,g], **Doerthe Tetzlaff**[g,h] **and Xinping Zhang**[e]

[a] *School of Civil Engineering, Sun Yat-sen University, Guangzhou, Guangdong 510275, China*
[b] *Southern Marine Science and Engineering Guangdong Laboratory, Zhuhai, Guangdong 519082, China*
[c] *Guangdong Engineering Technology Research Center of Water Security Regulation and Control for Southern China, Sun Yat-sen University, Guangzhou 510275, China*
[d] *National Centre for Groundwater Research and Training, Flinders University, South Australia SA5042, Australia*
[e] *College of Resource and Environmental Science, Hunan Normal University, Changsha 410081, China*
[f] *Northern Rivers Institute, School of Geosciences, University of Aberdeen, Scotland AB243UF, UK*
[g] *IGB Leibniz Institute of Freshwater Ecology and Inland Fisheries, Germany*
[h] *Department of Geography, Humboldt University Zu Berlin, Germany*
Email: wanghlong3@mail.sysu.edu.cn

Abstract: Since Professor Paul G. Jarvis proposed a scheme in 1976 that relates stomatal conductance with environmental variables, there have been numerous studies exploring the relationships for estimating transpiration (Ec). Vapor pressure deficit (D) and solar radiation (R) are dominant environmental factors influencing Ec, whilst air temperature (T) is deemed important but often neglected in model applications since D and T are exponentially correlated. Thus, it is uncertain whether to construct the Jarvis-type Ec models with both T and D included will improve model performance. Meanwhile, it is worth mentioning that most Jarvis-type models cannot simulate nocturnal sap flow which has been observed across a wide range of species and climates. Therefore, this study was firstly aimed at developing a generalized temperature stress function and testing its role in the Jarvis-type model, and further improving the model by modifying a widely used radiation function for nocturnal sap flow simulations. The results show that inclusion of a T-stress function for hourly sap flow simulations can avoid overestimation of daily peaks, and the modified Jarvis-type model was able to capture the nocturnal sap flow. These improvements revive the model for ecohydrological applications in a future climate where enhanced temperature effects and increasing nocturnal transpiration resulting from rising nighttime vapor pressure deficits are likely.

Keywords: *Transpiration, nocturnal sap flow, environmental changes, stomatal conductance, Jarvis-type model*

Estimating rainfall-runoff model parameters using the iterative ensemble smoother

F.R. Bennett [a] and **J. Doherty** [b]

[a] *Department of Environment and Science, Queensland Government, Australia*

[b] *Watermark Numerical Computing, Brisbane, Australia*

Email: frederick.bennett@des.qld.gov.au

Abstract: Catchment water quality models are an important tool for understanding the impacts of land management practice on the water quality of the receiving waters of the Great Barrier Reef lagoon. As part of the Paddock to Reef program the Great Barrier Reef Catchment Loads Modelling Program estimates average annual loads of key pollutants (sediment, nutrients and pesticides) for each of the 35 catchments draining to the Great Barrier Reef. Since catchment models assume that constituent generation and transport within the catchment is largely controlled by rainfall and runoff, it is imperative that the hydrology calibration approach underpinning the catchment model is rigorous and achieves the best possible results. Because catchment models are conceptual representations of very complex landscape systems any forecasts and predictions they produce will be subject to uncertainty and quantifying uncertainty is an important aspect of analysing model performance.

Various methods derived from a range of statistical frameworks have been applied to study uncertainty of rainfall-runoff models. Perhaps the most intuitive way of approaching uncertainty analysis is via the formalism of Bayes' theorem where some prior understanding of the model parameters is updated once exposed to relevant data. As elegant as Bayesian uncertainty analysis may be, there are practical limitations to implementing it. The equations defining Bayes' theorem often have no analytic solution, or at least one that is tractable, one must resort to numerical methods to complete the process. In practice, this usually involves a campaign of stochastically sampling from the Bayesian posterior distribution to construct a statistical facsimile. This can be a computationally exhausting process, particularly when an expensive model is used, the prior is significantly divergent from the posterior and a large number of parameters is involved.

Ensemble methods such as the iterative ensemble smoother (IES) have been developed to alleviate much of the computational overhead demanded by the uncertainty quantification of environmental models, particularly those that involve high dimensional parameter spaces. On the face of it, the IES would seem to fit very well with the problem presented by catchment water quality models but to date, there is very little evidence of this. In this study, we apply a Gauss-Levenberg-Marquardt form of the IES to the calibration and uncertainty analysis of a rainfall-runoff model. The IES is found to be an efficient and powerful method for conditioning model parameters and providing robust uncertainty estimates adhering to the spirit of Bayesian statistics.

Keywords: *Ensemble smoothers, Bayesian methods, uncertainty analysis*

Can spatial weighting of land use data improve our ability to predict stream water quality?

Xiaoyan Dai[a], **Yiwen Xu**[a], **Junjie Li**[a], **Shuijing Zhu**[a], **Danlu Guo**[a] **and J. Angus Webb**[a]

[a] *Department of Infrastructure Engineering, The University of Melbourne, Parkville, Australia*
Email: xiaoyand1@student.unimelb.edu.au

Abstract: Deteriorating water quality in streams and rivers has led to economic, environmental, and social impacts worldwide and has raised significant concerns. To assist management of stream water quality and catchments, a critical task is to improve the understanding and modelling capacity for stream water quality.

Many analyses have investigated the effects of catchment land use on stream water quality, but most of them have used proportions of land uses lumped at the catchment scale. Distance-weighted analyses treat land use parcels differently, depending on where they are within the catchment (Walsh & Webb, 2014). For example, it is expected that regions next to the stream would be more influential to stream water quality than regions that are further awayt. Such distance-weighted approaches allow explicit spatial representations of catchment land-use for the water quality modelling, which has the potential to improve water quality predictions. However, there is limited understanding on how different weighting functions affect the model performance, and how the use of weighting improves water quality prediction compared to the conventional lumped approach.

This research aims to understand whether spatial weighting of land use data improve water quality prediction, by developing predictive models for stream water quality with alternative spatial weighing models on catchment land use. We used the same dataset as a previous study by Lintern et al. (2018), which modelled water quality with lumped land use data at catchment scale, and compared the performances of models with land use considered in lumped and spatially weighted manners. The specific research questions we address are:

1. Are water quality models with spatial weighing of catchment land use outperforming the corresponding models without spatial weighing?
2. What is the best method for spatial weighing of catchment land use in predicting stream water quality?

To achieve this, we maintained consistency with the variables and model structure developed by Lintern et al. (2018). Six constituents (Total Suspended Solids, Total Phosphorus, Filterable Reactive Phosphorus, Total Kjeldahl Nitrogen, the sum of Nitrates and Nitrites and Electrical Conductivity) were analysed with data from 102 catchments across Victoria. When applying spatial weighting, we assume the influence of land-use via overland flow from the land parcel to the stream channel is different to that via in-stream transport to the sampling location (Walsh & Webb, 2014). We employed threshold, exponential and linear decay functions along the 'to-stream' and 'in-stream' flow paths and tested multiple parameterizations of the decay functions to identify the best spatial scale over which to consider influences of land use on water quality. The optimal model structure (including the decay function) was identified based on the Complete Akaike Information Criterion (CAIC).

The key findings are: 1) The predictions of all water quality constituents perform better with spatially weighted land use parameters, in terms of higher NSE and R^2 values, but improvements were marginal for some constituents; 2) Weighting worked better for conservative constituents (EC, TSS) compared to reactive ones (FRP, NOx); 3) Models using the threshold weighting function outperform the exponential and linear decay functions; 4) Weighting land use parameters with the highest coefficient do not always give the greatest improvement in model performance. This study suggests that NOx, TKN and FRP are not worth weighting spatially, and the richness of subsurface infrastructure should be considered for urban catchments.

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Keywords: *Distance weighting, stream water quality, Land use, statistical modelling*

Catchment-coast modelling for conjunctive management of eutrophication risks in the Hauraki Gulf and its tributaries

Sandy Elliott[a], Helen MacDonald[a], Linh Hoang[a], Christian Zammit[a] and Manawa Huirama[a]

[a]*National Institute of Water and Atmospheric Research, New Zealand*
Email: sandy.elliott@niwa.co.nz

Abstract: The Inner Hauraki Gulf/Tīkapa Moana ecosystem is facing proliferations of algae, de-oxygenation, reduced pH (acidification), reduced water clarity, and muddier sediments arising from past and current land-derived contaminant inputs. These effects are likely to be exacerbated by continued inputs and climate change. Freshwater systems feeding to the Gulf also face stressors such as deoxygenation and excessive macrophyte growth. Regional planning initiatives have called for predictive integrative models to help identify contaminant load limits for the Hauraki Gulf land-freshwater-marine system. These models need to incorporate the effects of climate change and mitigation systems used to reduce contaminant loads in the catchment (5858 km^2).

To address these management needs, NIWA is conducting coupled land, river and marine modelling to predict contaminant loads and concentrations and their impacts on freshwater and aquatic ecosystems, to address management questions such as nitrogen load limits, timescales for recovery, cost of load reduction, and implications of climate change.

The modelling approach extends and couples models for land generation of contaminants, river transport and effects, and marine transport and eutrophication to address management needs. In the first year, existing models were coupled and applied to scenarios of source load reduction and climate change. The models were:

- WRTDS - A statistical method to calculate daily time-series of river loading from historical measurements
- CLUES – An annual-average catchment model
- Rating curve disaggregation – A statistical method to derive daily catchment load estimates from mean annual loads and flows, which were predicted with the hydrological model TopNet.
- SWAT – A dynamic physics-based catchment model, was applied to predict changes in nutrient loading due to climate change scenario in a small dairy catchment (Toenepi)
- Delwaq – A river hydraulics and contaminant transport model was coupled with SWAT for a trial catchment.
- ROMS – A sophisticated model for coastal hydrodynamics and eutrophication.

The pilot modelling study has demonstrated the feasibility of linking catchment and coastal models to predict coastal eutrophication responses over a decadal time-scale, and using these models to assess implications of nutrient source reduction and climate change. Some example preliminary findings are:

- Nitrogen loading is dominated by the Waihou and Piako catchments (73% of catchment loading to the gulf), although loading per unit catchment area is more evenly spread across rivers.
- The climate change scenario indicated reductions in catchment nitrogen loading associated with runoff reductions. This is a preliminary result based on a single scenario. Since predicted river flows and loading decreased by the same magnitude, the concentrations will not change much overall.
- Catchment loading reductions required to meet river nitrogen targets at monitoring sites were modest (16%), leading to only small reductions in algal concentrations in the Gulf. The catchment reductions are preliminary results based on simplified modelling and depend on the selection and locations of target concentrations.

In future work, we are: shifting to using SWAT for the full catchment; improving river eutrophication models with emphasis on dissolved oxygen; and improving the marine model to take factors such as remineralisation of legacy benthic enrichment; and deeper interaction with catchment and marine managers.

Keywords: *Water quality, eutrophication, nitrogen, catchment modelling, coastal modelling*

Using mixed method design to quantify uncertainty in constituent load estimates

Baihua Fu [a], **Joseph Guillaume** [a], **Ryan Turner** [b], **Alex Villa** [b], **Reinier Mann** [b], **Catherine Neelamraju** [b], **Rohan Wallace** [b], **Stephen Wallace** [c], **David Waters** [c] and **Anthony Jakeman** [a]

[a] *Institute for Water Futures and Fenner School of Environment & Society, The Australian National University, Canberra, ACT 2601, Australia, Email: baihua.fu@anu.edu.au*
[b] *Department of Environment and Science, Brisbane, Qld, Australia*
[c] *Department of Resources, Brisbane, Qld, Australia*

Abstract: Authoritative and concise information on uncertainty in constituent loads is important in communicating confidence limits for a monitored load, and supporting the interpretation and evaluation of catchment water quality model outputs. Existing studies investigating load estimate uncertainty typically involve comparing scenarios of sampling frequency and load estimation methods with a reference "true" load estimation, often based on high-resolution data. Uncertainty associated with measurements, especially concentrations, is often overlooked.

This presentation describes a case study employing a mixed method design (Teddie and Tashakkori, 2010) to quantify uncertainty in load estimates at Sandy Creek at Homebush, located in the Plane basin in the Mackay Whitsunday region of Queensland. The aim of the project is to develop a comprehensive method of estimating load uncertainty, and provide a starting point for discussions about uncertainty reduction. The uncertainties from five major sources were included: concentration measurements, flow measurements, load estimation methods, Beale ratio bias correction functions, and sampling frequency (Figure 1). Qualitative methods were used to elicit the critical decision forks contributing to uncertainty in concentration and flow measurements. Quantitative methods were employed to simulate uncertainties sourced from load estimation methods, Beale's ratio bias correction functions, sampling frequency, and the combined uncertainty in annual load estimates.

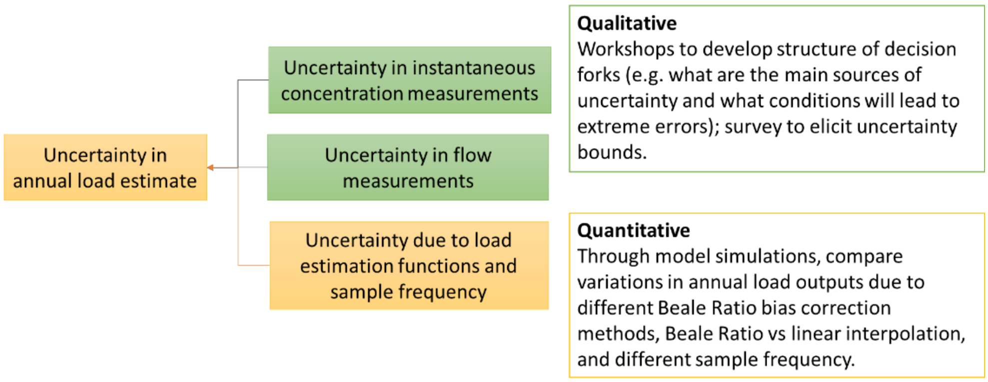

Figure 1. Methods used for investigating uncertainty in annual load estimates

Preliminary results suggest the estimated uncertainty in annual load estimates are very high. Concentration measurements and sample frequency account for most of the uncertainty in these annual load estimates. Opportunities to better estimate and reduce uncertainty are likely to focus on sample repetitiveness at different flow conditions, concentration uncertainty estimates, uncertainty associated with sampling frequency and approaches to aggregate the different sources of uncertainty (e.g. using distributions rather than bounds).

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Keywords: *Water quality, nutrients, load estimates, catchment modelling*

Evaluating the variation between daily and sub-daily sediment models under climate change at Cardinia

L Goss [a, b], **L. Cetin**[b], **A. Ladson**[c] **and A. Lintern**[a]

[a] *Faculty of Engineering, Department of Civil Engineering, Monash University, Melbourne, 3800, Australia*
[b] *Jacobs, Water Resources New Zealand and South East Australia, Melbourne, 3800, Australia*
[c] *Moroka, Pty Ltd. Northcote, 3070, Australia*
Email: lucyjgoss@gmail.com

Abstract: It is unclear what impact climate change will have on the processes controlling sediment yields, and concerns have been raised that using an inappropriately long timestep for simulating sediment loads under future climate change scenarios may result in misleading predictions in sediment loads (Cetin, et al., 2021). Pollutant loads are strongly associated with rainfall intensities and peak runoff rates and given these processes occur at short timescales they are often difficult to estimate when using daily average rainfall and flow rates (Francey, et al., 2011). This study aims to inform water quality modelling choices by evaluating the variability of sediment load estimates caused by assessing the impact of temporal resolution on estimates of sediment export from catchments. The catchment of Cardinia, Victoria has been used to trial the development of a methodology that can be expanded to catchments across Melbourne for a broader understanding of how climate change could impact sediment loads.

The Cardinia catchment has an area of approximately 122 km^2 and drains into Western Port, Victoria. In order to quantify the effects of modelling at different timesteps, two simple empirical models of sediment export using rainfall as an input parameter have been calibrated for the catchment. The empirical models were adapted from a study by Francey, et al. (2011), with one model operating at a daily timestep, and the second model at a hourly timestep. A rainfall data cube developed by Melbourne Water and Hydrology and Risk Consulting (HARC) was used to extract the rainfall data for both models which included historical and climate change factored rainfall data (Vic 'High' scenario). The dataset scales rainfall intensities, as well as reducing the mean annual rainfall following the DELWP Climate Change modelling guidelines.

The models have been calibrated against water quality data recorded at Gauge 228228: Cardinia Creek at Chasemore Road Cardinia township (supplied by Melbourne Water). The gauge recorded hourly turbidity and flow, which were used to estimate hourly sediment loads using regression parameters developed by Wilkinson, et al. (2016). According to the objective functions employed (Nash Sutcliff Efficiency, Pearson Correlation Coefficient, and Root Mean Square Efficiency), the initial calibration process did not yield a desirable fit to the measured data however further calibration options are being explored.

At an annual scale both the daily and sub-daily models produced similar changes in load under climate change. However, at the event scale, the daily model performed poorly compared with the hourly model. More research is needed to validate these initial findings, however the methodology developed in this case study may help tackle the uncertainty of the required timestep in sediment modelling for climate change. This approach should be explored for a wider variety of catchment characteristics, in particular urban catchments where transport of sediment loads are typically more affected by high intensity rainfall events.

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Keywords: *Sediment modelling, climate change, temporal variability*

How does riverine water quality vary across Australia? A continental synthesis of water chemistry states, export patterns and export regimes

Danlu Guo[a], Anna Lintern[b], Shuci Liu[c], Camillé Minaudo[d], Kefeng Zhang[e], Rémi Dupas[f], Ulrike Bende-Michl[g] and Clément Duvert[h,i]

[a] *Department of Infrastructure Engineering, University of Melbourne, Victoria, 3010, Australia*
[b] *Department of Civil Engineering, Monash University, Victoria, 3800, Australia*
[c] *School of Geographical Sciences, Nanjing University of Information Science & Technology, Nanjing, 210044, China*
[d] *EPFL, Physics of Aquatic Systems Laboratory, Margaretha Kamprad Chair, Lausanne, Switzerland*
[e] *Water Research Centre, School of Civil and Environmental Engineering, UNSW Sydney, Kensington, NSW 2052, Australia*
[f] *INRAE, L'institut Agro, UMR 1069 SAS, 35000 Rennes, France*
[g] *Bureau of Meteorology, 2601 Canberra, Australia*
[h] *Research Institute for the Environment and Livelihoods, Charles Darwin University, Darwin, NT, Australia*
[I] *National Centre for Groundwater Research and Training (NCGRT), Australia*
Email: danlu.guo@unimelb.edu.au

Abstract: Water quality management and policy development need be to be supported by good understanding of the spatial variability in the mean concentrations of water quality parameters and their temporal dynamics. The inter-annual mean concentrations of water quality parameters inform the expected water chemistry states for individual catchments. The relationships between these concentrations and discharge reveal further information on the export patterns and export regimes. Previous studies have explored the spatial variation of water chemistry states and the export patterns/regimes at local to regional scales. However, we still lack understanding on these spatial variations at continental scales, especially across many catchments representing contrasting climate zones, hydrologic regimes, and land use conditions. This study aims to improve the understanding of the spatial variation in the states, export patterns and export regimes of stream water quality across Australian catchments. The wide range of hydro-climatic regimes and land use/land cover conditions in Australian catchments make this continent the ideal experimental field to gain such an understanding. We analysed a total of 578 catchments across the five major climate zones within the Australian continent – arid, Mediterranean, temperate, subtropical and tropical zones. We designed a series of studies using a national consistent, data-driven approach to understand these spatial variations and to identify the key drivers of these variations. We focused on key water quality parameters of interest for Australian catchment management, namely: electrical conductivity, total suspended solids, total nitrogen, total phosphorus, nitrate-nitrite, soluble reactive phosphorus and calcium.

For the inter-annual mean concentrations, we found significant differences across climate zones. Generally, we found higher spatial variability than temporal variability in water chemistry concentrations. In contrast, the export regimes and patterns of water chemistry are generally consistent across climate zones. This suggests that the export regimes and patterns could be controlled by the intrinsic properties of individual constituents rather than by the spatial/climatic properties.

We explored other potential drivers of the spatial variation of the export patterns, considering variations in the catchment hydrologic regimes and other catchment characteristics such as land use, land cover, geology, and soil composition. Catchment land use has high impact on average concentration, while catchment topography is more important for concentration-discharge relationship. The identified key factors have varying effects on water quality spatial responses across different climate zones. The inter-annual mean concentrations are found more predictable across space than the export patterns. Within each climate zone, variations in the export patterns are strongly influenced by the catchment-level summary (mean and variation) of baseflow contribution. This highlights the potential link between enhanced water chemistry export in catchments with greater variation of instantaneous baseflow contribution, and thus having more variable water sources and flow pathways. These findings can potentially improve the predictive capacity of riverine water quality to support nation-wide catchment management.

Keywords: *Concentration-discharge relationship, C-Q slope, stream, catchment management*

INVITED PAPER

EXTENDED ABSTRACT ONLY

Application of the improved catchment water quality plugin CLOE in eWater Source

Joel Hall[a], Gayan Gunaratne[b] and Baihua Fu[c]

[a] *Aquatic Science Branch, Department of Water and Environmental Regulation, Joondalup, 6919, WA Australia*
[b] *Environment Group, BMT Commercial Australia, Pty Ltd, Osbourne Park, 6017, WA Australia*
[c] *Institute for Water Futures and Fenner School of Environment & Society, The Australian National University, Canberra, ACT 2601, Australia*
Email: joel.hall@dwer.wa.gov.au

Abstract: The Catchment constituent Load Estimates model (CLOE) was developed to address limitations in the standard eWater Source water quality modelling functionality. CLOE aims to improve processes such as constituent generation, filtration and transport to ensure that they are of a relevant complexity required to inform management decisions.

An extensive review of 42 water quality models and modelling platforms in Australia and worldwide (Fu et al, 2019) found that no single model or platform contained the right complexity (including data requirement) and flexibility required for decision making by Australia's water quality catchment managers. Compared to the existing water quality modelling modules in eWater Source, CLOE has significantly improved the representation of constituent generation and land-to-water delivery processes, and enabled the inclusion and exploration of management practices in water quality impacts. More specifically, the enhancements include:

- For generation: adding capacity to include user-specified sources of constituents (e.g. fertilizer, plant decay, hillslope erosion, fire-induced erosion, etc) for each Functional Unit or landuse.
- For land-to-water delivery: adding capacity to empirically model constituents land-to-water delivery ratio based on flow and management drivers, instead of using specified delivery ratio.
- Loss pathway: consider five interconnected constituent loss pathways: soil to outside the system (e.g. denitrification), soil to stream, soil to groundwater, groundwater to outside the system, groundwater to stream.
- Adding dynamics in constituent soil stores, groundwater stores and link/river stores.

A CLOE plugin was developed in eWater Source, and applied to the Ludlow catchment, in south-west WA. Previous modelling studies have indicated that dairy and beef pasture comprises the majority of TN and TP inputs within the Ludlow catchment (more than 95%), and these landuses were the focus of the CLOE implementation. Whole-farm nutrient data including fertiliser and feed inputs (and timing) was taken from farm surveys, and converted to CLOE inputs. Paddock data from fertiliser management programs, including soil Phosphorus Buffering Index (PBI) and Colwell-P, were also used to develop model inputs. Two long-term water quality sampling and flow gauging locations in the upper and lower Ludlow River were used to calibrate the rainfall runoff model, and to derive loads that were used to assist in the calibration of CLOE. In addition, paddock-scale lysimeter data was used to verify soil-store fluxes. Management scenarios, such as fertiliser rate and timing changes, or the application of soil amendments could then be applied to select landuses or subcatchments, to evaluate changes to catchment loads, and progress towards load reduction targets.

This proof-of-concept demonstrates that CLOE can be applied and utilised to make management decisions in a practical context, using available data collected from a suite of catchment management and water quality programs. The formalised development of systematic data collection and calibration regime that utilises both hard and soft data would be of benefit for further application of CLOE. Furthermore, if CLOE is going to be applied more broadly, it is a priority to improve the accessibility of the CLOE plugin by enhancing the user interfaces for model calibration, data entry, scenario development and results analysis in eWater Source.

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Keywords: *Water quality, nutrients, catchment modelling, CLOE, eWater Source*

INVITED PAPER

EXTENDED ABSTRACT ONLY

Shifts in stream salinity during and after prolonged droughts: A Hidden Markov Modelling approach

Natalie Kho[a,b], Anna Lintern[a], Tim Peterson[a] and Danlu Guo[c]

[a] *Department of Civil Engineering, Monash University, Victoria, Australia*
[b] *SMEC Affiliation*
[c] *Department of Infrastructure Engineering, University of Melbourne, Victoria, Australia*
Email: anna.lintern@monash.edu

Abstract: For the design and implementation of effective water quality management strategies, we must understand the key processes driving temporal patterns in water quality. Previous studies have indicated that rainfall-runoff responses in catchments can be impacted significantly by prolonged droughts, and for many years after the drought (Peterson et al., 2021). The impacts of prolonged drought on water quality have been less investigated. The few studies that have investigated the relationship between drought and water quality trends have found decreased sediment levels, increased salinity, varying nutrient responses based on whether the source is point or diffuse (Caruso, 2002; Mosley, 2015). These previous studies have used pre-determined start and end-dates of drought to identify the impact of the drought on water quality. As a result, there is limited understanding of any lagged effects of drought on water quality, which could be important for catchments or constituents with long travel time. Not only do we require more understanding of the impacts of prolonged drought on water quality, we need to do this using an approach that does not rely on assumed start and end dates for droughts to assess the lag times between changes in streamflow and changes in water quality patterns.

This study addresses these knowledge gaps using Hidden Markov Models (HMMs); specifically, the R-package *HydroState*. These are flexible models that can identify (i) different states in water quality given the distribution of the time-series data; and (ii) the probability of being in a particular water quality state at a certain point in time (Zucchini and MacDonald, 2009). In this study we focused on long-term records of riverine water quality to assess whether there are multiple steady states of water quality, which correspond to the Millennium Drought (~1995-2010). We use salinity as a case study and focus on eight catchments from the state of Victoria (South-East Australia. Using HMMs, we modelled the monthly salinity loads at the eight catchments for the period of 1991-2015, using precipitation data as an input. As a reference of the hydrological conditions to interpret any shift in salinity, we also modelled the shift in streamflow at these eight catchments using precipitation data.

The HMMs indicated that a two-state model best fitted the observed salinity loads. This means that at all catchments salinity loads were at a 'normal' state in 1993, and then shifted to a 'low state' after this time. For six out of the eight sites, this shift occurred after the Millennium Drought commenced. Indeed, comparison of the timing in the shift in salinity load states with the shift in runoff states indicated that generally, the shift to the lower salinity state occurred after the shift to a lower 'runoff' state. Therefore, it is likely that the shift in salt loads during and after the drought is due to a reduction in the contribution of saline groundwater. The HMMs also suggest that water quality states do not necessarily recover to pre-drought levels after the conclusion of the drought. At all eight sites, 'low' salinity states were observed even after the conclusion of the Millennium Drought in 2010. This is consistent with the runoff non-recover shown by Peterson et al. (2021).

These findings emphasise the complexity in salinity responses during and after prolonged droughts, and the need to consider these shifts in water quality states when designing catchment management strategies. This is particularly urgent given the likelihood of increased frequency and severity of droughts in the future.

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Keywords: *Water quality, statistical methods, extreme events, modelling, resilience, Millennium Drought*

EXTENDED ABSTRACT ONLY

Advances in long-term water quality monitoring through data fusion

Trung Dung Nguyen[a], **Wei Xiang**[a], **Ulrike Bende-Michl**[b], **Zhen He**[a], **and Rajalakshmi Rajasekaran**[a]

[a] *Cisco-La Trobe Center for AI and IoT, La Trobe University, Australia*
[b] *Bureau of Meteorology, Australia*
Email: t.nguyen9@latrobe.edu.au

Abstract: Monitoring water quality is essential to understand the suitability of water for a range of purposes: human consumption and sanitation, sustaining or improving ecological sites, agricultural and industrial productions, etc. Water quality can change rapidly due to impacts from compound events, such as bush fires and floods or can deteriorate slowly over long periods, for example due to climate change. However, water quality monitoring in Australia faces many challenges: firstly, there is no nationally agreed routine water monitoring framework in place to systematically observe water quality conditions across the country. Secondly, different sampling regimes often means that water quality data is difficult to compare nationwide. Additionally, monitoring water quality on a national scale in Australia is virtually impossible due to the remoteness and inaccessibility of many water bodies, causing many water quality issues to remain undetected.

To overcome the limitations in water quality monitoring and assessment, this project aims to research long-term water quality monitoring and analysis capabilities by exploring the fusion of satellite images and in-situ water quality observations. Images of inland water bodies from space can provide insights into the spatial and temporal distributions of ecological phenomena that indicate water quality, such as harmful algae blooms, blackwater events and acid sulphate soils (Fan et al., 2021; Pahlevan et al., 2021). On the other hand, in-situ data can reveal pH levels, salinity, nitrogen levels, and many other important water quality parameters. Therefore, this project will fuse two-dimensional satellite image data and one-dimensional in-situ data into an integrated metric to measure the quality of water for monitoring and forecasting purposes.

We propose to focus our research on addressing the following two research problems: i) data fusion: can deep learning models accurately predict water quality using a combination of satellite images and in-situ water parameter data? Furthermore, can we train the model to provide accurate predictions even when one or more parameters are missing? And ii) forecasting: can we train a deep learning model to accurately forecast future water quality parameters? This model can be used to predict when and where water bodies might degrade beyond repair and alert for early conservation efforts to intervene.

This presentation will share an overview of the proposed method: the most popular deep learning architecture for extracting features from images is the Convolutional Neural Network (CNN). This type of neural network will learn certain features from the satellite images and map them to ecological phenomenon in the water. The next step is to build a multitask learning model, so that the shared model body can learn from both in-situ sensor data and satellite data and create multiple heads, each of which can predict each of the SDG-6 parameters to determine the water quality, which is the goal.

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Keywords: *Machine learning in water quality, data fusion, water quality monitoring and assessment*

Modelling to determine key drivers of water quality off sugarcane paddocks in the Great Barrier Reef catchment

B. Power[a], **M. Shaw**[a], **M. P. Vilas**[a], **M. Farr**[b], **M. Thompson**[b] **and M. Poggio**[b]

[a] *Department of Resources, Queensland Government, Australia*
[b] *Department of Agriculture and Fisheries, Queensland Government, Australia*
Email: brendan.power@resource.qld.gov.au

Abstract: Reducing pollutants, such as nitrogen and sediment from sugarcane lands, in the Great Barrier Reef catchment is important for protecting the resilience of the World Heritage listed ecosystem. Modelling is used to predict the change in water quality in response to typical changes in sugarcane management. To accomplish this, workshops were conducted with groups of 15 to 20 industry experts in each of the major sugarcane growing regions and a range of typical agronomic management, appropriate for each region, was elicited. APSIM was used to simulate a farm in each of the three regions Burdekin Delta, Mackay, and Tully, to estimate the expected pollutant loads from each farm. Each *in silico* farm is represented by a combination of soil, climate and the range of management derived from the workshops. Simulated pollutants include erosion and dissolved inorganic nitrogen (DIN), from both leaching below the root zone and in runoff. To quantify and rank the effect of changes in management on pollutants exiting farms least squared regressions were estimated using model output. Results are presented for the key management of nutrient and irrigation rates, tillage, and fallow crop scenarios. We found the rate of applied mill mud had the greatest effect on DIN exiting sugarcane paddocks both via leaching and in runoff (Figure 1) and the amount of tillage had the greatest effect on erosion (Figure 2).

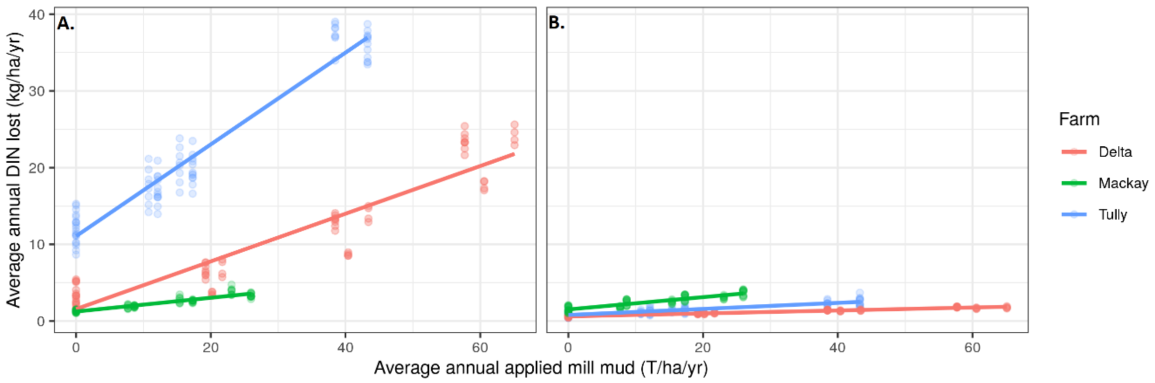

Figure 1. Simulated average annual leached DIN (A) and DIN in runoff (B) by average annual applied mill mud for a subset of management and a typical farm in each region (colour).

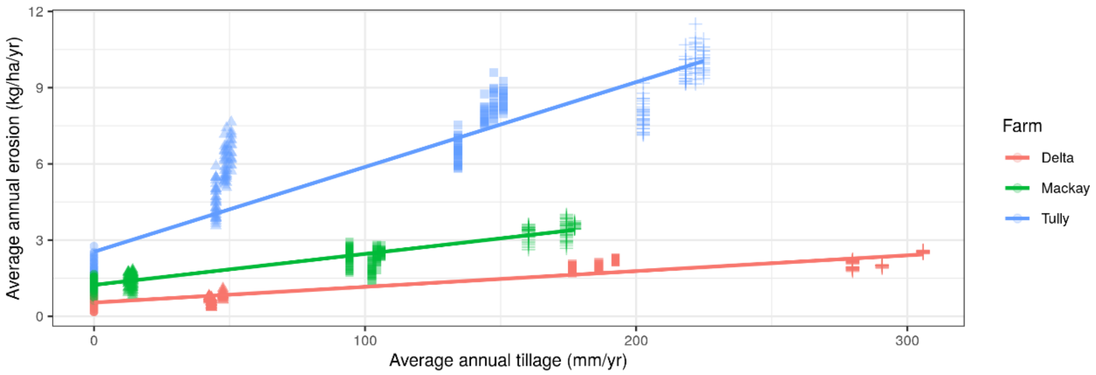

Figure 2. Average annual erosion (T/ha/yr) by tillage (mm/yr). Point shape indicates different tillage scenarios.

Keywords: *Water quality, APSIM, fertiliser, tillage, dissolved inorganic nitrogen*

Sensitivity analysis of a travel time distribution approach for modelling stream salinity

Z. Riazi [a], A. W. Western [a], U. Bende-Michl [a]

[a] *Department of Infrastructure Engineering, The University of Melbourne*

Email: a.western@unimelb.edu.au

Abstract: Understanding the effect of model parameters on simulations is important for model calibration. In this paper we applied the "Variogram Analysis of Response Surfaces" (VARS-TOOL) framework (Razavi *et al.*, 2019) to analyse the sensitivity of parameters in a conceptual water quality model, constructed based on a travel time tracking approach. The sensitivity of stream salinity (electrical conductivity) simulations to parameter values was analysed for the Scotts Creek, SW Victoria and the Duck River NW Tasmania, Australia, catchments for 20 years.

This water quality model couples the StorAge transit time modelling approach (Harman, 2015; Benettin and Bertuzzo, 2018; Visser et al., 2019). The StorAge approach estimates dynamic transit time distributions for stream water. These were coupled with two alternate approaches to model electrical conductivity:1) a catchment with a cyclic salt balance and dynamic equilibrium between rainfall as a source and stream flow as a sink, in which evapoconcentration of salt acts as the main process changing concentration. 2) age of water in the catchment storages determines salinity of water, C_{age}, such that $C_{age}(T) = C_0 + (C_\infty - C_0)(1 - e^{-T/\lambda})$, where C_0 is the concentration at age T=0, $C\infty$ is the concentration at infinite age and λ is the timescale of salinity increase with age.

Where an explicit solute balance is used, the most important parameter differs between the catchments with the age mix of evapotranspired water (controlled by α_{ET}) being most important in Scotts Creek and rainfall concentration, C_{rain} being most important in Duck River. In Scotts Creek the age mix of low flow (controlled by β_{min}) and a flow transformation parameter, q_{power}, are also important, while in Duck River the age mixes of both evapotranspiration and low flow are important. When salinity is simulated assuming a relationship between concentration and age, the most important parameters are C_∞ and λ. Parameter sensitivity is more consistent for the simulation approach using an age-concentration relationship.

Table 1. Parameter sensitivity for Scotts Creek and Duck River Catchments.

Storage Concentration	Catchment	Most Sensitive Parameter	Most Sensitive Group Parameter	Least Sensitive Parameters
Age based	Scotts Creek	C_∞	C_∞, λ	C_0, β_{ET}, α_{min}
	Duck River	C_∞	C_∞, λ	C_0, β_{ET}, α_{min}
Solute balance	Scotts Creek	α_{ET}	α_{ET}, β_{min}, q_{power}	S_0
	Duck River	C_{rain}	C_{rain}, α_{ET}, β_{min}	q_{power}, S_0, β_{ET}

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Keywords: *Sensitivity analysis, travel time distribution approach, modelling stream salinity*

Opportunistic emulation of computationally expensive simulations via Deep Learning

Conrad Sanderson [a], Dan Pagendam [a], Brendan Power [b], Frederick Bennett [c] and Ross Darnell [a]

[a]Data61 / CSIRO, Australia
[b]Department of Resources, Queensland Government, Australia
[c]Department of Environment and Science, Queensland Government, Australia
Email: firstname.lastname@data61.csiro.au

Abstract: With the underlying aim of increasing efficiency of computational modelling pertinent for managing and protecting the Great Barrier Reef, we perform a preliminary investigation on the use of deep neural networks for *opportunistic* model emulation of APSIM models, by repurposing an existing large dataset containing the outputs of APSIM model runs. The dataset has not been specifically tailored for the model emulation task. We employ two neural network architectures for the emulation task: densely connected feed-forward neural network (FFNN), and gated recurrent unit feeding into FFNN (GRU-FFNN), a type of a recurrent neural network. Various configurations of the architectures are trialled. A minimum correlation statistic is employed to identify clusters of APSIM scenarios that can be aggregated to form training sets for model emulation.

We focus on emulating four important outputs of the APSIM model: (i) *runoff* – the amount of water removed as runoff, (ii) *soil_loss* – the amount of soil lost via erosion, (iii) *DINrunoff* – the mass of dissolved inorganic nitrogen exported in runoff, and (iv) *Nleached* – the mass of nitrogen leached in water draining to the water table. The GRU-FFNN architecture with three hidden layers and 128 units per layer provides good emulation of *runoff* and *DINrunoff*. However, *soil_loss* and *Nleached* were emulated relatively poorly under a wide range of the considered architectures; the emulators failed to capture variability at higher values of these two outputs.

While the opportunistic data available from past modelling activities provides a large and useful dataset for exploring APSIM emulation, it may not be sufficiently rich enough for successful deep learning of more complex model dynamics. Design of Computer Experiments may be required to generate more informative data to emulate all output variables of interest. We also suggest the use of synthetic meteorology settings to allow the model to be fed a wide range of inputs. These need not all be representative of normal conditions, but can provide a denser, more informative dataset from which complex relationships between input and outputs can be learned.

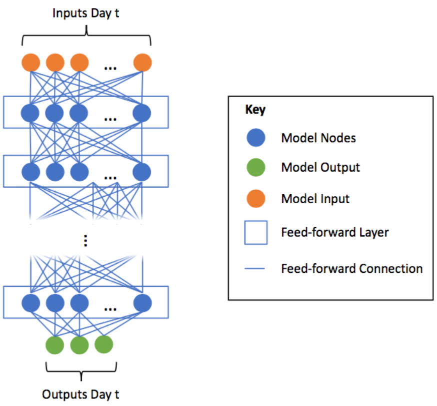

Figure 1. Example of a Feed-Forward Neural Network (FFNN) for model emulation.

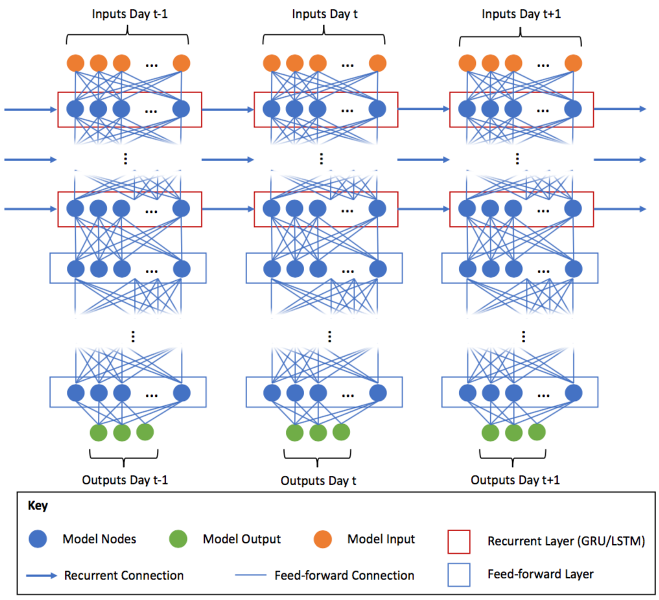

Figure 2. Example of a recurrent neural network feeding into FFNN.

Keywords: *Surrogate models, model emulation, deep neural networks, recurrent neural networks, APSIM*

Characterising soil-surface nutrient excess to improve prediction of nutrient exports from agricultural land

Robert Sargent [a], **Andrew Western** [b], **Perran Cook**[c] **and Anna Lintern** [a]

[a] *Department of Civil Engineering, Monash University, 3800, Australia*
Email: Robert.Sargent@monash.edu
[b] *Department of Infrastructure Engineering, University of Melbourne, 3010, Australia*
[c] *Department of Chemistry, Monash University, 3800, Australia*

Abstract: Predicting the export of nutrients (nitrogen (N) and phosphorus (P) to waterways in response to changes in land use and climate will be vital for ensuring the future health of ecosystems and sustainability of water resources. This project seeks to develop a modelling tool to predict waterway nutrient exports, incorporating improved representations of nutrient sources, transport processes, biogeochemical transformations and Best Management Practices.

Preliminary investigations aimed to better understand how agricultural land use contributes to waterway nutrient export. This will inform development of the source component of the modelling tool. The study was conducted in a region of intensive irrigated agriculture in South Eastern Australia, where nutrient losses impair water quality by stimulating algal blooms. Substantial investment in Best Management Practices (BMPs) has occurred to mitigate these losses. Nutrient sources within the study area were investigated using a soil-surface nutrient budget. Historic industry-specific nutrient use information was collated from regional farmer extension programs, agricultural productivity assessments and published literature. This was combined with parcel-scale land use data to estimate nutrient excesses on agricultural land between 2010 and 2020. Nutrient concentration and flow data available from stations upstream and downstream of the study region between 2015 and 2020 allowed a comparison with nutrient losses via drainage.

Preliminary results indicate a gradual increase in soil-surface excess N (primarily due to intensification of dairy production), and comparatively stable P excesses (Figure 1). Nutrient loss via surface drainage exhibited substantial interannual variability largely due to variations in flow. Variability of N export was greater than that of P. Drainage loss was equal to 0.7% of calculated soil-surface excess N, and 1.0% of excess P between 2015 and 2020. These low comparative losses (McKee *et al.* 2000) may be due to effective BMP implementation, though climatic variability and the limited period of stream monitoring are also likely contributing factors. Uncertainties in input data also have substantial potential to influence results, and will be a focus of future refinements to both the soil-surface budget and riverine export calculations.

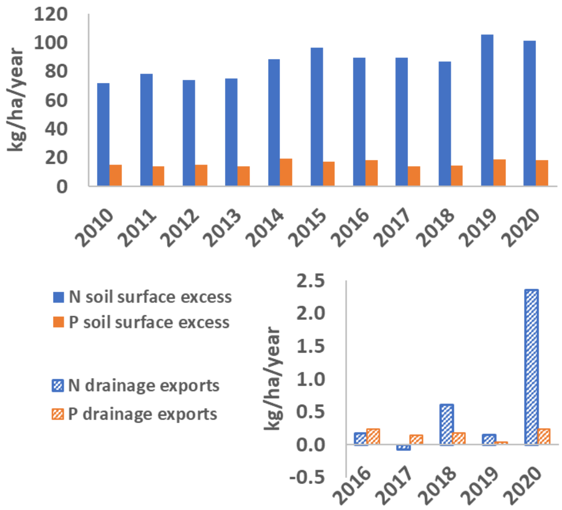

Figure 1. Top: Annual soil-surface nutrient excesses for the study area. Bottom: Nutrient exports from the study area via drainage.

This work uses a land-use specific nutrient budgeting approach to improve representations of nutrient pollution sources. This will contribute to improving predictions of nutrient export from agricultural land, and subsequently the prediction of receiving water quality.

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Keywords: *Nutrients, water quality, agriculture, land use*

Revised models for the proportion of suspended sediments in hillslope soil loss – an empirical understanding

D. Mark Silburn [1,2]

[1] *Department of Resources, Queensland, 2 Centre for Agricultural Engineering, University of Southern Queensland, Queensland*

Email: mark.silburn@resources.qld.gov.au

Abstract: This paper investigates the proportion of suspended sediment in hillslope erosion using measured data and presents preliminary models. The P2R Dynamic-SedNet (PD-SedNet) model calculates the proportion of suspended sediment in runoff from hillslope erosion as directly proportional to the proportion of dispersed silt and clay in the surface soil. However, many soils are composed of and erode as a large proportion of aggregates of primary particles. Exceptions occur where the surface soil is dispersive, non-cohesive (e.g., loose sand), or where the sediment is eroded from a hard-set surface. Laboratory data for bare, rainfall wet surface soils indicate that the proportion of fine particles (<0.125 mm) increases until surface soil silt and clay is 50 % and then flatten at about 25% suspended sediment. Suspended sediment is lower than the PD-SedNet equation for soil silt and clay greater than 15%. An equation (modified Loch/Lu) was fitted to these laboratory data. Suspended sediment data for eight plots and catchments in Queensland and six in SE Asia with bare soil were also plotted against soil silt and clay, and the PD-SedNet and modified Loch/Lu equations. Two relationships emerged: 1) data for dispersive, mulga, non-cohesive and hardsetting soils fit around the PD-SedNet line, and 2) data for "aggregated soils" fit around the modified Loch/Lu line. For aggregated soils, when soil silt and clay is 60%, PD-SedNet proportion of suspended sediment is 60% while the data/Loch/Lu equation indicates it is ~25%. That is, the PD-SedNet equation gives a large overestimate for bare, aggregated soils.

However, much of Queensland's cropping and grazing land is not bare. Data from two studies in grazing and three in cropping show that the proportion of suspended sediment increases with increasing cover. The proportion of suspended sediment is strongly related to ground cover for grazing and cultivated catchments, but the relationship differed for different soils. As cover increases, the proportion of suspended sediment approaches the PD-SedNet line. However, at high enough cover the proportion of suspended sediment exceeds that calculated with the PD-SedNet equation. For example, for the Wallumbilla Grey Vertosol, the soil silt plus clay is 48%, giving a PD-SedNet estimate of suspended sediment of 48% whereas the Wallumbilla suspended sediment can vary from 17 to 80% depending on cover. A more general method is needed to estimate the proportion of suspended sediment. This method needs to account for the effects of soil and cover as shown here, and other factor known to affect the proportion of suspended sediment, such as prior land use and slope. The results presented here are at small plot and catchment scale; an unresolved issue remains that coarser sediment will continue to be deposited with increasing scale. At what scale should suspended sediment be defined? Future work should concentrate on deriving more relationships with cover and finding a method for predicting these relationships based on commonly available data and resolving the scale issue.

Keywords: *Cover, Great Barrier Reef (GBR), soil erosion, sediment delivery, sediment size*

Modelling stream salinity using a water-age based approach

A. W. Western [a], **Z. Riazi** [a], **U. Bende-Michl** [a]

[a] *Department of Infrastructure Engineering, The University of Melbourne*
Email: a.western@unimelb.edu.au

Abstract: It is widely recognized that the flow response is much more rapid than the transport response in catchments and this leads to marked damping and long delays in water quality response compared with hydrologic response, yet this is rarely explicitly included in water quality models. An impediment is the rarity of water age data for streamflow; however, stream electrical conductivity data is often collected and is a potential surrogate tracer of water age. Here we examine whether salinity data can be used in calibrating an age-based water quality model and compare two alternative modelling approaches for this.

Stream salinity is modelled using two approaches based on age-ranked storage simulations (Harman, 2015) of water transport through the Duck River catchment, Tasmania. Age-ranked storage simulations calculate a water balance for an ensemble of storages that represent each water age separately. This results in water age distributions for each of a) water stored in the catchment, b) evapotranspired water and c) streamflow. These distributions vary dynamically. Stream salinity is then simulated using either 1) a solute mass balance assuming a fixed rainfall concentration, conservative transport through the catchment and including the effects of evapoconcentration or 2) an assumed relationship between water age and concentration.

These models were applied to ~18 months of continuous salinity (electrical conductivity) data from Duck River Tasmania over 2008-2009 using a 12 hour time step. Figure 1 shows an example of results for the age-based model calibrated for the 2008 water year. Nash-Sutcliffe efficiencies (NSE) varied between 0.87 and 0.95 for calibration and 0.72 and 0.91 for validation. Most of the degradation in NSE from calibration to validation was due to bias during the validation period. Performance was slightly better and more consistent for the age-based approach. Simulated median stream water ages varied between the simulation options from 0.5 and 1.25 years for low flow conditions and 1 week and 4 months for high flow conditions. Median ages for water in storage varied from 9 months to 18 months for low flow and 4.5 and 12 months for high flow conditions. While water ages are plausible, they are quite variable and require testing against direct measures of water age.

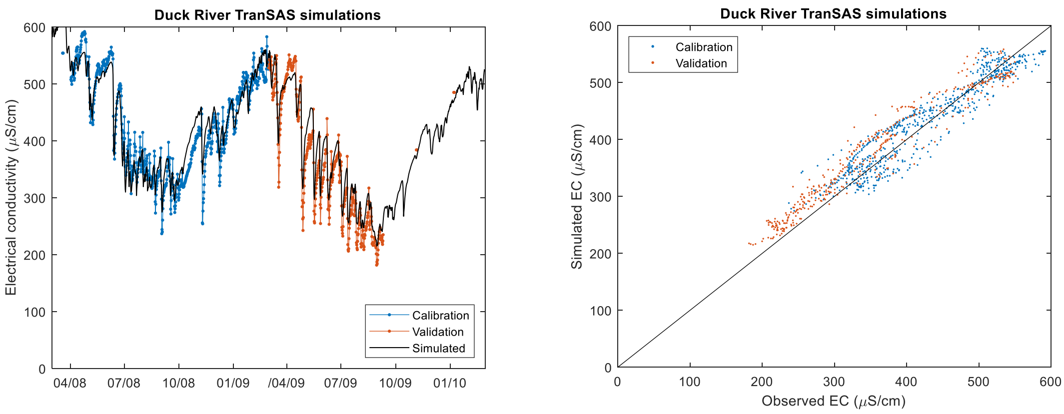

Figure 1. Simulated and observed time series (left) and scatter plot of simulated and observed electrical conductivity (EC) for Duck River with the age-based solute model with calibration from 1/3/08 to 28/2/09 and validation from 1/3/09 to 28/2/09.

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Keywords: *Water quality, travel time, water age, salinity*

The use of modelling in design of wastewater subsurface drip irrigation

F.J. Cook[a,b,c] **P. Gearing**[d]**, S. Bennett**[e] **and R Oakley**[e]

[a] Freeman Cook & Associates Pty Ltd, [b]School of Food and Agriculture, The University of Queensland, [c]Australian Rivers Institute, [c]Griffith University, [d]NexGen Water Ltd, New Zealand, [e]Stantec Dunedin, New Zealand,

Email: freeman.j.cook@gmail.com

Abstract: A methodology for the use of modelling in designing a wastewater land treatment scheme is presented. This uses analytical models to determine the depth and spacing of the drippers. From the dripper spacing and the wastewater volume the number of drippers, the area to be irrigated can be calculated an d a provisional design developed. The wastewater nitrogen concentration along with the average plant uptake was used to estimate the timing between irrigations. This led to further refinement of the provisional design with the number of blocks in the irrigation area and engineering layout such as valves etc.

The results from the analytical modelling were used to determine the spatial domain for the numerical modelling and an a few initial layouts. The numerical modelling used HYDRUS2D with axisymmetric coordinates and was run for a 7 year period. This approach allows the different layouts to be tested against the consent requirements. A flow chart of the systematic approach taken is shown in figure 1.

This approach was used for the Te Anau subsurface dripper irrigation (SDI) scheme, which is used as an example. The consent requirement was based on the leaching of nitrogen beyond a depth of 2 m. The sensitivity of the results to the depth and spacing between the drippers and the time between wastewater irrigations showed that only the spacing had a significant effect on the nitrogen leaching.

The results from the numerical modelling were used to design the final layout and the area required for irrigation and accompanying ungrazed area. The ungrazed area required to achieve a nitrogen load to the groundwater below a consent level was determined using the results from the modelling. The methodology used here of incorporating both analytical and numerical modelling in designing a wastewater land treatment scheme offers a systematic approach to design such schemes.

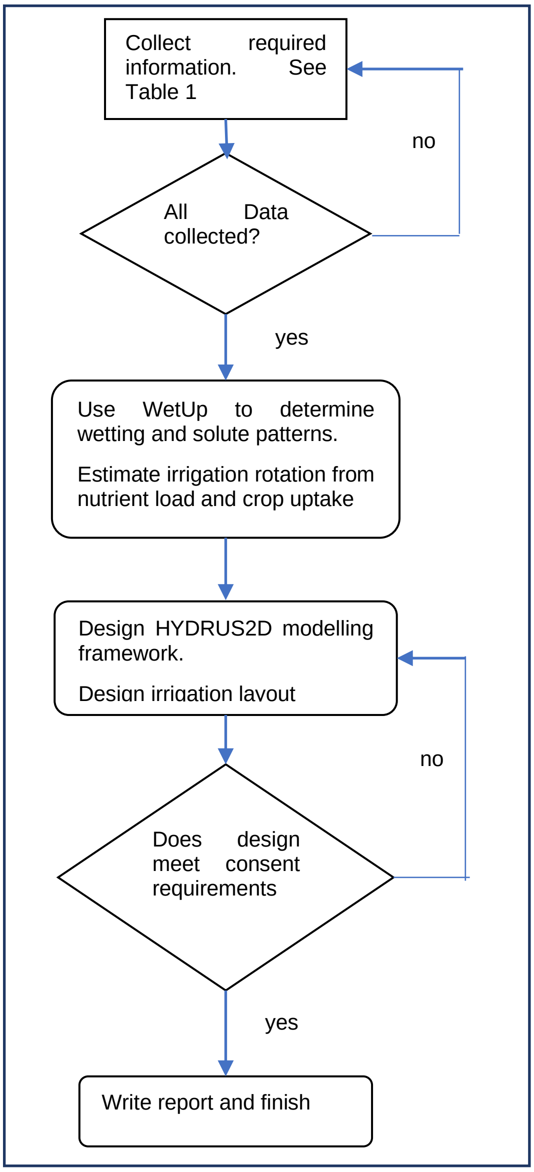

Figure 1. Flowchart for wastewater subsurface irrigation design

Keywords: *Land treatment, wastewater, HYDRUS2D, subsurface drip irrigation, modelling*

A model based on DOC data for determination of alum dosing for drinking water treatment

H. Daraei [a,e], **J. Awad** [a,d], **E. Bertone** [b], **R.A. Stewart** [b], **C.W.K. Chow** [a], **J. Duan** [a,c] **and J. van Leeuwen** [a,c]

[a] Scarce Resources and Circular Economy (ScaRCE), UniSA STEM, University of South Australia, Adelaide, SA, Australia, [b] Griffith University, Gold Coast, QLD, Australia, [c] Future Industries Institute, Adelaide, SA, Australia, [d] CSIRO Land & Water, Adelaide, SA, Australia, [e] Environmental Health Research Center, Kurdistan University of Medical Sciences, Sanandaj, Kurdistan, Iran;
Email: Hiua.Daraei@mymail.UniSA.edu.Au

Abstract: In this paper, the development of a model is described which is designed for the determination of alum dosing needed for controlled removal of dissolved organic carbon (DOC) in drinking water treatment. Development of the model is intended to be applied for feed-forward prediction of required alum dosing, using raw water DOC data along with turbidity data.

To develop the DOC-based model, 72 samples were collected from 16 different surface water sources. Seventeen samples (from 15 different sources) were used for jar tests and model development. The remaining samples from the same water sources were used for testing the model performance in a comparison study with a previously established model. That model, named mEnCo is based on other parameters, i.e., ` colour and UV light absorbance at 254 nm (A_{254}), and with turbidity data.

For the new model development, data of DOC, A_{254}, colour and turbidity were acquired for the raw water samples and following treatment with alum in jar tests. These data were then analysed for changes in DOC removal rates with increasing alum dosing. From an understanding of the DOC removals behaving as an 'exponential decay' and the distinction between the coagulable and non-coagulable (recalcitrant) portions of the DOC pool, a hybrid model based on the removal mechanism of DOC is proposed here. An exponential decay function was found to be suitable for the fitting of data of residual DOC following treatment with an increase in alum dose. The average R^2 (adjusted) value for the model fitted to the jar test data of the samples studied is 0.96 ± 0.05.

A dose set at a target of 85.1% coagulable DOC removal was found to equate to an 'enhanced' dose (EnD), where DOC removal in treated drinking water is practically optimized. This value was obtained from the average of the 17 waters studied using the jar test procedure. Determinations using the model were compared to the EnD obtained experimentally through jar testing and the EnD values obtained through the mEnCo software. The results show a comparable (and slightly improved) performance to the original mEnCo software for the newly developed DOC-based model, based on the EnD data acquired through jar testing. The new DOC model also shows potential suitable capability for prediction of the EnD for waters with very high organic matter content as may occur under extreme climate conditions. These particular samples (5 out of 17 samples jar tested) were out of the designed operational limits of the mEnCo model (i.e., 14 mg L^{-1} DOC, 0.55 cm^{-1} absorbance) and were not included for comparison. A comparative study between the new DOC model and mEnCo using 33 out of 55 testing samples which were in the operational range of the mEnCo model demonstrated the comparative predictivity for these two models, which use different input data (R^2=0.92).

A software referred to as 'WTC-DOC_Coag' was developed using the new DOC-based model with intent as an extended option to the previously established WTC-Coag software. It is proposed that the DOC-based model, with the capability to provide a comparable performance for dose prediction using input signal from an online DOC analyser, has the potential for online feedforward coagulant control. This might also be in combination with other model systems which use different input signals, then increasing the overall robustness of the control system. Validation of the WTC-DOC_Coag performance for suitability at drinking water plants is required and planning for this is to include domestic and overseas plants.

Keywords: *Drinking water treatment, coagulation-flocculation process, dissolved organic carbon (DOC) based model, coagulant dosing control, Online control*

Evaluation of MUSIC for application in Singapore tropical climate

Harsha Fowdar [a,b], **Teck Heng Neo** [c], **Jiangyong Hu** [c] **and David T. McCarthy** [a,b]

[a] *Department of Civil Engineering, Monash University, 3800, Victoria, Australia* [b]*CRC for Water Sensitive Cities, Monash University, Australia* [c]*Department of Civil & Environmental Engineering, Faculty of Engineering, National University of Singapore, Singapore*
Email: harsha.fowdar@monash.edu

Abstract: A wide range of stormwater control measures (or green infrastructure, GI), including bioretention systems, wetlands, grassed swales, have been developed and implemented in the last few decades to mitigate the negative impacts of urban stormwater on receiving water hydrology and quality. These function to store, infiltrate, detain or treat storm runoff across a diverse range of scales and settings. They are growing in popularity across the globe not only in their stormwater treatment capacity but also as climate change adaptation strategies. Stormwater GI models are important tools to inform the planning of these systems (type, design, size), in the most efficient and cost-effective manner. MUSIC (Model for Urban Stormwater Improvement Conceptualisation), an example of such a tool, is widely used in Australia for urban drainage planning. MUSIC continuously predicts treatment of sediments and nutrients through different stormwater measures, such as wetlands and swales, through the Universal Stormwater Treatment Model (USTM); this is based on the first order decay treatment equation (K-C* model through different CSTR cells). Treatment through bioretention systems is a combination of both the USTM model and experimentally derived regression curves.

Although the software is widely used, there have been limited studies that validate its accuracy and performance under different design and climatic conditions. This information is vital not only for translation of the model to other regions with different climates, design and inflow pollutant characteristics but also to provide key information for future model development in the field. This study, thus, evaluates MUSIC for a field scale bioretention system, stormwater wetland and grassed swale operating under Singapore tropical climate. The model was evaluated for systems monitored over a period of at least one year and includes a range of events encompassing different temporal and wetting-drying periods. Events included both natural storm events as well as more controlled field tests.

Results showed that the treatment modules were able to simulate outflows and effluent pollutant concentrations (Figure 1) reasonably well for cumulative event volumes and loads. Cumulative event volumes were mostly within 25% of their measured values. Across the three pollutants, cumulative outflow TP and TN were predicted with higher accuracy (within 30% of their measured values) compared to outflow TSS. The models were found to be significantly underestimating outflow TSS loads as a result of greater variability in measured TSS concentrations across events (Figure 1).

A comparatively lower level of success was obtained for simulating the outflow hydrograph and pollutographs of the different inflow and drying/wetting conditions. The swale module fared the best in this respect with a Nash-Sutcliff coefficient, E of 0.83 for the outflow rates. The bioretention flow module showed promise (e.g. it was mostly able to predict the shape and timing of peak flows reasonably well), however may under-perform for systems whose design deviates from best practice, for e.g. in the case of an over-sized system. These results, altogether, indicate that MUSIC model can be transferred to other locations provided that management decisions be concentrated on long term modelling efforts as these tend to reduce the model uncertainties.

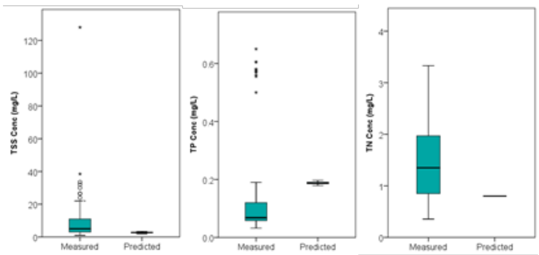

Figure 1. Range of measured outflow pollutant concentrations (TSS, TP and TP) and predicted EMCs across the tested events for the bioretention module

Keywords: *Green infrastructure, water quality, urban stormwater*

Utility of remote sensing for understanding water quality changes in small urban waterbodies

Shuang Liu [a], William Glamore [b], Bojan Tamburic [a] and Fiona Johnson [a]

[a] *Water Research Centre, University of New South Wales, Sydney, 2052, Australia*
[b] *Water Research Laboratory, University of New South Wales, Sydney, 2052, Australia*
Email: shuang.liu@unsw.edu.au

Abstract: Water colour can be an indicator of water quality. The colours of small urban shallow waterbodies are affected by geophysical, anthropogenic, and climate factors. There is a pressing need for effective strategies for monitoring water quality in waterbodies with sparse sampling records. Remote sensing techniques have becoming increasingly popular for water quality monitoring in large inland lakes. In this study, we investigate if such techniques are also useful to detect the spatial and temporal patterns of water colour changes in small constructed waterbodies. This information could help water managers understand the drivers of water colour change and system health.

Here more than 200 small constructed shallow waterbodies in south-eastern Australia were analysed for water colour spatio-temporal patterns using Sentinel 2 and Landsat 5, 7 and 8 imagery for more than 30 years. We investigated how climate factors impact the water colour variability using a non-parametric model. We found that some of the lakes have strong seasonal cycles in water colour whilst others have less regular patterns of variability. For many of the lakes, water colour variability can be explained by the temperature and rainfall over the past 30 days. We also analysed spatial patterns of water colour, and clustered them based on catchment characteristics. The results from the study will help water managers identify which groups of lakes will be most impacted by climate drivers, and therefore provide guidance on strategic monitoring plans in a changing climate.

Keywords: *Water colour, remote sensing*

A sensitivity analysis of a water quality model for a constructed wetland

M. E. Roberts [a b], **J. Lu** [b], **E. Kavehei** [b] **and M. F. Adame** [b c]

[a]*School of Environment and Science, Griffith University, Queensland, Australia*
[b]*Australian Rivers Institute, Griffith University, Queensland, Australia*
[c]*Coastal and Marine Research Centre, Griffith University, Queensland, Australia*
Email: m.roberts2@griffith.edu.au

Abstract: Excess nitrogen in storm runoff in agricultural regions contributes to poor water quality in coastal and marine environments, including the Great Barrier Reef. Constructed wetlands are one mechanism by which land holders and governments in tropical north Queensland are combating poor water quality. Wetlands are known to be effective at promoting nitrogen amelioration – reducing the nitrogen concentration of outflows relative to their inflows. Mathematical models of nitrogen processes in wetlands are useful for exploring the conditions under which wetlands are most effective in order to guide wetland design and management. Understanding the relative importance of, and model sensitivity to, the various biogeochemical processes (within the wetland) and the boundary conditions (influxes to the wetland) is critical to target monitoring and further research where it will best reduce uncertainty and improve decision making.

This paper presents a sensitivity analysis of a single-box compartment model for nitrogen within a wetland in tropical north Queensland. Five coupled ordinary differential equations describe the masses of nitrate (NO_3-N), ammonium (NH_4-N), dissolved organic nitrogen (DON), particulate organic nitrogen (PON), and suspended sediment (SS) within the wetland and includes terms for the release and transformation of the nitrogen forms within the wetland. The sensitivity analysis includes an exploration of 21 model parameters, namely the transfer rate constants and half saturation constants, the temperature rate factor, and the nitrogen concentrations in rain, through both a vary one-at-a-time (OAT) analysis and an all-at-the-same-time analysis. The sensitivity of the model to the boundary conditions, that is the mass influxes of the various nitrogen forms and sediment entering the wetland, was explored using a OAT analysis applying a fixed proportional variation to the mass influx time series for each of NO_3-N, NH_4-N, DON, PON, and SS. The sensitivity was measured using the metrics of cumulative removal of each of total nitrogen (TN), the different nitrogen forms (NO_3-N, NH_4-N, DON, PON), and SS over a four month study period for a case study wetland.

The all-at-the-same-time analyses demonstrated that while the degree of removal showed considerable variation across the parameter space, the majority (90%) of scenarios had net TN removal, with all scenarios showing net NO_3-N and net PON removal. DON was generated within the wetland under all scenarios, and ammonium was generated in 93% of cases. Understanding the conditions under which net TN generation could occur will be essential for effective management of treatment wetlands.

TN removal was PON driven, and hence very sensitive to those parameters that drive PON removal, namely particle size and density. While the absence of re-suspension processes will lead to an over-estimation of PON removal, high PON influxes indicate that settling ponds to reduce PON inflow may be a useful strategy to improve wetland performance. Considering the internal processes, after settling TN was most sensitive to the ammonium release rate resulting from the mineralisation process. Ammonium was more sensitive to sediment release rates and plant uptake processes over the nitrification processes, most likely due to the anaerobic conditions that prevailed within the wetland. Sensitivity (within the top 10) to the temperature rate factor was also observed for all nitrogen forms (and SS); further investigation of temperature impacts is therefore warranted, particularly in wetlands threatened by climate change.

The TN removal performance, although dominated by PON, is the combination of the different removal forms. All nitrogen forms showed sensitivity to their influx values, however the degree of sensitivity varied markedly. Ammonium was most sensitive to influx masses, with a 20% variation in influx resulting in as much as 1000% change in the removal. In contrast, DON variation was within 100%, NO_3-N within 20%, and PON within 5%.

Keywords: *Nitrogen, denitrification, treatment systems, Great Barrier Reef, mineralisation*

Mitigation knowledge gaps: a call to arms

Annette Semadeni Davies and Sandy Elliott

National Institute for Water and Atmospheric Research (NIWA), New Zealand
Email: annette.davies@niwa.co.nz

Abstract: Over the past few years, I have been involved in a number of modelling projects using catchment-scale steady-state models for central and regional government to predict the impact of various mitigation measures on freshwater quality. While there has been much written about the need for reliable input and calibration data requirements for water quality model development and testing, less attention has been paid to data needed for scenario creation. In my presentatoin, I want to share the experiences I have had setting up mitigation scenarios for water quality models due to gaps in our knowledge about the efficacy and implementation of mitigation measures.

I have chosen riparian planting as an example since this mitigation measure has been a key scenario in most of the projects I have worked on. It is a widely accepted measure and an integral part of national and regions strategies for improving freshwater quality both due to bank strengthening, and stock exclusion (Hughes 2016). However, there is little quantitative information either internationally or in New Zealand about how well riparian planting reduces the loads of sediment, nutrient and bacteria reaching waterways. For example, while riparian buffers can be very effective at removing nitrate from soils (up to 70%), the amount of removal is highly variable spatially and seasonally due to differences in soil properties, plant types, buffer width and climate. However, there is insufficient data to quantify how nitrate removal varies (personal communication, Lucy McKergow, June 2021). Another issue is that the research that has been done has tended to be at the farm-scale and the effects of mitigation at the catchment-scale are largely unknown. Moreover, we lack information on the current implementation of mitigation measures to set model baselines. For riparian planting, we do not know where have streams banks been planted, which plants have been used or buffer width. The data that are available include industry reports and self-reporting by farmers (e.g., via the bi-annual Survey of Rural Decision Makers)[1]. These data are not purpose collected and, at best, available only regionally.

This has meant that the model applications used simple future state scenarios that are based on a professional judgement as much as on evidence. For example, in the absence of data on the relative efficacy of riparian planting with fencing for stock exclusion, our national E. coli modelling (Semadeni-Davies and Elliott 2017; Semadeni-Davies *et al.* 2020), we used a flat 10% increase in *E. coli* removal compared to fencing on its own.

These experiences are not unique to riparian planting or indeed to steady-state modelling. Dynamic models require the same access to information to create mitigation scenarios. The lack of fundamental knowledge on the implementation and efficacy of mitigation measures is worrying given the high political, cultural and economic stakes involved in water management in New Zealand and the increasing reliance on modelling to inform water management. The challenge for us as modellers is to push for basic research and data collection on mitigation measures so that our scenarios are robust.

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***Keywords**: Scenario modelling, riparian planting, data requirements*

Modelling of a five reactor Activated Sludge cascade process using ASM #1

S. Watt [a] **and M. Nelson** [b] **and F. Hai** [c] **and H. Sidhu** [a]

[a]*School of Science, UNSW Canberra, PO Box 7916 Canberra BC, ACT 2610, Australia*
[b]*School of Mathematics and Applied Statistics, University of Wollongong, NSW 2522, Australia*
[c]*Strategic Water Infrastructure Lab, School of Civil, Mining and Environmental Engineering, University of Wollongong, NSW 2522, Australia*
Email: simon.watt@adfa.edu.au

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

We analysed the biological treatment of a wastewater when a cascade of five reactors were used. Operating conditions were investigated in which the first reactor was not aerated. The second reactor could be either be aerated or not aerated. The remaining reactors were aerated. The process configuration included one settling tank and one recycle step. Both of these were placed after the final reactor in the cascade.

We used the hydraulic retention time (HRT) as the bifurcation parameter and investigate how the total nitrogen concentration in the effluent (TN_e) stream depended upon the operation of the recycle step and the state of aeration in the second reactor. When the reactor configuration *included* an ideal settling tank, the total nitrogen concentration is defined as

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

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

We explored a number of different aspects of a five reactor cascade.

1. We compared the performance of reactor configurations up to five reactors, with the first reactor not aerated. The qualitative behaviour was the same, with three regimes of HRT: for low HRT, the system was in a washout state, where the process failed, then a transition, or bifurcation, when the heterotrophic biomass species were present, and finally another transition, when both the heterotrophic and autotrophic biomass species were present. The final transition occurred at lower HRT as the number of reactors in the configuration was increased. There was also an improvement in the performance.

2. We explored the effect of varying the HRT in each reactor and compared the performance with an equal HRT configuration. For the most of total HRT values, the equal HRT configuration offered close to the best performance. For a total HRT near the transition where the heterotrophic and autotrophic biomass species were present, the equal HRT configuration offered close to the worst performance.

3. We explored the effect the configuration with a recycling step, compared to a configuration where there was no recycling step. We found that the configuration with a recycling step outperformed one without. However, the performance improvement occurred up to critical recycling rate. For higher recycling ratios, the performance deteriorated.

4. Finally, we explored the effect of either aerating the first and second reactors, while aerating the other three reactors, not aerating the first reactor and aerating the second or not aerating the first and second reactors. We found that it was better to not aerate the first reactor and aerate the remaining reactors.

Keywords: *Activated sludge, modelling, recycling, stirred tank, wastewater*

Modelling the fate and transport of trace elements from three ports in the marine coastal waters of the Abu Dhabi Emirate

Louise C. Bruce[a,b], Anbiah Rajan[c], Ala'a Ahmad Rezeq[c], Michael Barry[a], Hamid Fanai[a], Kreshan Heera[a], Emma McCall[a] , Kabir Suara[a], Kyle Woodborne, Mitchell Smith[a], Ian Teakle[a] and Shaikha Al Hosani[c]

[a] *BMT Commercial Australia, Brisbane, AUSTRALIA.*
[b] *The University of Western Australia, Perth, Australia.*
[c]*Environment Agency – Abu Dhabi, Abu Dhabi, United Arab Emirates.*
Email: kabir.suara@bmtglobal.com

Abstract: The marine coastal waters of Abu Dhabi provide significant economic, social and environmental benefits to the Emirate. Contamination from trace elements associated with port operations, including transport activities, industry and urban discharges are a focus of marine water quality management for environmental regulators. As heavy metal contaminants are non-degradable, they persist in the marine environment and can cause major issues to marine biota from bioaccumulation. Mapping contamination factors and calculating indexes of geoaccumulation and pollution loads are essential practices for environmental regulators to target management policies towards risk minimisation strategies. A coupled 3D hydrodynamic and water quality model was developed to simulate the fate and transport of heavy metals from three ports along the Abu Dhabi coastline, Mussafah Port, Khalifa Port and Al Mirfa Port.

Tracers were released simultaneously from the three ports as a proxy for trace element contaminants over a month-long simulation using two alternative climatic forcing in the summer and winter periods. Maps of contamination factors, impact footprints and regions of influence were compared across the three ports with differing influencing factors observed. Contaminants released from Mussafah channel were mostly contained within the low circulating shallow waters of the port and surrounds whereas contaminants from Al Mirfa and Khalifa ports were transported alongshore and to a lesser extent towards the deeper waters of the Gulf. Contaminants from Al Mirfa were predominantly transported in a westerly direction and from Khalifa in a north-easterly direction. The results of the simulated patterns of fate and transport will be compared against measured concentrations of trace metals to elucidate the probability of source and loadings to improve understanding and target mitigation actions.

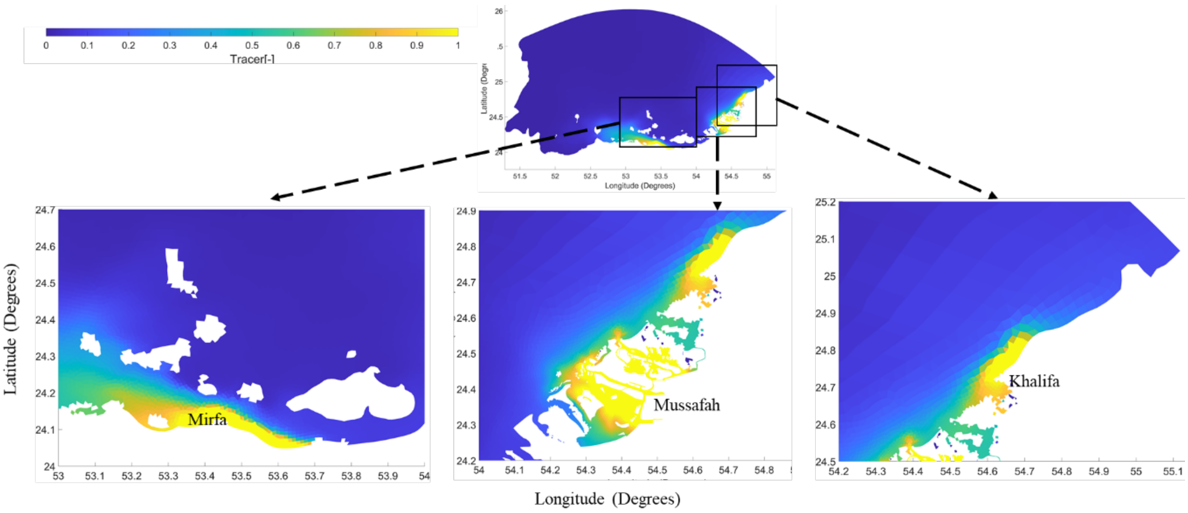

Figure 1. Median tracer concentrations next to the bed

***Keywords**: Trace elements, ports, numerical model*

EXTENDED ABSTRACT ONLY

Integrated modelling assessment of nutrient cycling and water quality in the Peel-Harvey Estuary

Peisheng Huang [a,b], **Matthew R. Hipsey** [a,b], **Brendan Busch** [a] **and Karl Hennig** [c]

[a] *Aquatic Ecodynamics, UWA School of Agriculture and Environment, The University of Western Australia, Crawley WA 6009, Australia.*
[b] *UWA Oceans Institute, The University of Western Australia, Crawley WA 6009, Australia.*
[c] *Department of Water and Environmental Regulation, Perth WA 6842, Australia.*
Email: peisheng.huang@uwa.edu.au

Abstract: The Peel-Harvey Estuary system, located within the south-west Australian region, is surrounded by a large catchment of ~11,940 km^2, including the coastal city of Mandurah which is one of the fastest growing cities in the state. The estuary received excessive anthropogenic nutrient loading from the catchment and has exhibited signs of environmental stress due to eutrophication. At the same time, the Peel region experienced a drying climate followed by a rapid decline in runoff to the estuary. The need to effectively balance the water quality status with development opportunities to support economic and societal growth in the Peel-Harvey Estuary region confronts managers as a 'wicked problem', and requires knowledge of the past and present state of the estuarine condition and an understanding of how it will responds to environmental stresses.

The changes in the key water quality attributes and nutrient budgets of Peel-Harvey Estuary were analysed through integration of long-term monitoring data and a high-resolution water quality response model. The analysis validated in detail the model performance against the available data from 1979–2018 and the estuary response to climate change, catchment loading, and construction of Dawesville Cut, an artificial channel built in 1994 to improve the ocean flushing, was assessed. The water quality presented clear seasonal changes following the Mediterranean climate (wet winters and dry summers), and inter-annual shifts driven by the drying trend. The reconstruction of nutrient load and its relative nutrient species partitioning over time shows reduction in load due to decreasing inflows and slight decreases in the flow-weighted nutrient concentrations. The high-resolution water quality response model is able to reproduce the spatiotemporal variability in the key water quality attributes and processes across the region from rivers to lagoons and channels. Nutrient budgeting analysis within the estuary was resolved with the water response model, which has shown the opening of the Dawesville Cut effectively improved the ocean flushing and, on average, improved the TN and TP export efficiency, with the nutrient export via the Cut now about 2–3 times of that via the Mandurah Channel. The results have also shown the amount of nutrient retention is dependent on the annual flow volume the estuary receives, and therefore maybe sensitive to forecast projections due to drying climate. Zonal response models were used to identify local controls on metabolism, which showed locations near the channels were less sensitive to the catchment inputs, whilst the Harvey Estuary response displayed a stronger salinity and phytoplankton biomass response to the catchment inputs compared to Peel Inlet.

Keywords: *Water quality, estuary management, modelling, environmental data analysis*

EXTENDED ABSTRACT ONLY

Linking adaptive catchment and lake models in real-time to guide autonomous monitoring

N. Hutley [a], **N. Deering** [a], **A. Grinham** [a], **B. Gibbes** [a], **and S. Albert** [a]

[a] *School of Civil Engineering, The University of Queensland, Brisbane, 4072, Australia*
Email: nicholas.hutley@uq.net.au

Abstract: As the complexity, frequency and magnitude of pressures on water resources escalates, more advanced monitoring and modelling tools are required to guide management. Accessible live online data networks for in-situ and remote sensing of water resources are emerging as essential tools for operational management of these environmental systems. Data from these types of systems are also increasingly used to support the development of models which provide additional information to water managers. However, as we seek to understand and predict responses to an uncertain future, we increasingly rely on modelling to support decision making. Contemporary design and deployment of these monitoring systems, which is the subject of significant investment globally, is heavily dependent on spatially static monitoring nodes located using expert judgement informed by models rooted in historic datasets. Moreover, the investment required in these monitoring activities and knowing when enough data has been collected in any given environment is not well understood. Further to this, the training and evaluation of models using data from these system-blind environmental sensor networks are themselves usually limited in the accurate capture of information across the vast space and within the timescales of process significance that exist in the environment. This limitation is largely the result of trade-offs between budgets, project timelines, technological capabilities and regulatory monitoring requirements, which can lead to monitoring data missing key features from crucial moments to best characterise system drivers and responses within model parameter and state spaces. With ongoing developments in the fields of machine learning, as well as autonomous or remotely operable monitoring systems, there exists an opportunity to develop and implement the techniques of an adaptive learning environmental modelling feedback framework. This adaptive approach to modelling is able to infer the present state of an ecosystem from real-time monitoring data that can be dynamically collected for not only enhanced research and management value, but also for reducing model uncertainty).

Here we present the first integrated live modelling and monitoring framework in a southeast Queensland drinking water reservoir and surrounding catchment. The system utilises both a simple lumped parameter catchment model using a publicly available real-time streamflow data infrastructure network linked with ACCESS operational weather forecasting (BoM, n.d.), and a community weather station to infer and adapt the parameters of a catchment model (Boughton, 2004). This adaptive catchment modelling along with the meteorological forecast and live data was coupled with an adaptive three-dimensional model (Hodges & Dallimore, 2016) of the receiving waters (Lake Baroon, Queensland) using real-time fixed water profile monitoring data infrastructure as well as manual and autonomous spatially flexible model-guided monitoring. The novelty of this approach compared to previously developed real-time systems is in adaptive learning based on the amalgamation of available data sources, as well as the ability to integrate monitoring and modelling into a feedback loop where the adaptive modelling can guide future monitoring that is then consumed by the model learning process to improve the robustness of model training and meet the challenges of water resource management in an uncertain future.

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Keywords: *Catchments, adaptive learning, receiving waters, real-time data, autonomous monitoring*

Modelling methane emissions from lakes and reservoirs: case study of Lake Kinneret

K. Kurucz [a], **M.R. Hipsey** [a] **and P. Huang** [a]

[a] *School of Agriculture & Environment, University of Western Australia, Perth, 6009, Australia*
Email: kamilla.kurucz@research.uwa.edu.au

Abstract: Aquatic systems are responsible for 6–16% of global emissions of methane, a potent greenhouse gas. Methane concentration in the atmosphere is rising continuously, prompting the need for a better understanding of freshwater methane sources and sinks. To date, the global methane budget is based on up-scaling emissions from individual lakes resulting in erroneous freshwater methane emission estimates.

Methane is produced in the anoxic sediments of lakes and is emitted to the atmosphere via different pathways (Figure 1). These include diffusion, ebullition (bubbling), storage flux and advection through aquatic vegetation, all regulated by different physical, chemical, and biological factors. As a result, methane fluxes significantly vary both within and across systems. Due to its stochastic nature, ebullition is ever challenging to quantify and is generally disregarded from the global methane budget.

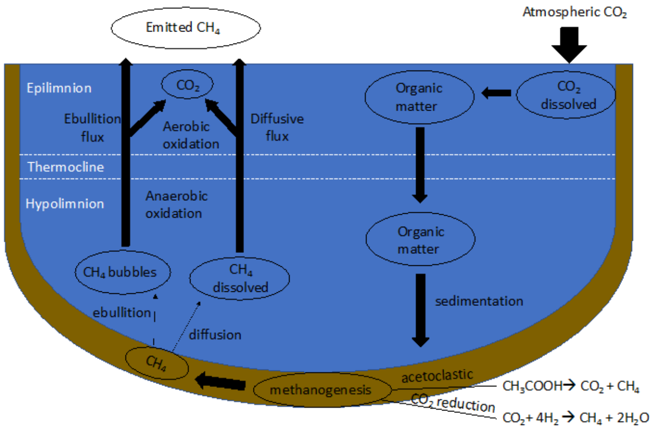

Figure 1. Key processes involved in methane production and methane emission in a stratified lake.

To improve methane emission estimates from freshwater, process-based models can be used that enable the simulation of each pathway separately. The aim of this study is to simulate methane emissions from a focus site. This is done through the development of a methane module in the Aquatic Ecodynamics (AED) modelling library which is applied to Lake Kinneret. Whilst Lake Kinneret is a single focus of this study, applying the developed methane model to a site with previously existing monitoring and modelling data will contribute to the building of an open-source general methane model.

In this study, the one-dimensional General Lake Model (GLM) was coupled to the AED modelling library to simulate the thermal dynamics and dissolved oxygen concentration of Lake Kinneret. The methane sources and sinks in the AED carbon module include diffusion, aerobic oxidation, and atmospheric gas exchange. To simulate ebullition, a new algorithm was added to the model. The ebullitive flux in this algorithm varies according to temperature and water level changes. The bubbles released from the sediments either dissolve in the water column or are directly emitted to the atmosphere.

The vertical temperature profile of the lake was successfully reproduced, with a Root Mean Square Error (RMSE) of 1.5 °C (~5%). The model has appropriately resolved the oxygen dynamics, except for the metalimnetic oxygen minimum, with an RMSE of 2.99 mg/L (~20%). The RMSE between the observed and simulated methane concentrations was 56 mmol/m^3 (~10%). The great annual and within system variations of the methane fluxes are captured well by the model. However, surface methane concentrations are repeatedly overestimated during holomixis. Lastly, the model simulates the seasonality of ebullition well, however, it doesn't capture its stochastic nature reported in the literature.

Process-based models have the ability to account for the variability in lake characteristics and capture the interannual and within system variations in methane emissions. However, to move away from site-specific ebullition models, it is crucial to develop new general ways to parametrise ebullition, enabling its applicability across a gradient of systems.

Keywords: *Biogeochemical modelling, freshwater methane emissions, ebullition*

Solving the puzzle of mercury in Lake Macquarie: Using hydrodynamic modelling to understand sources of mercury from coal-fired power plants

Anna Lintern[a], **Larissa Schneider**[b], **Maxwell Warren**[c], **Paul Winn**[d], **Lauri Myllyvirta**[e], **Sara Beavis**[b], **and Bernd Gruber**[f]

[a] *Department of Civil Engineering, Monash University, Victoria, 3800, Australia*
[b] *Archaeology and Natural History. Australian National University, Coombs Bld. 9, 2600, Canberra, ACT, Australia*
[c] *Fenner School of Environment and Society. Australian National University. Coombs Bld. 9, 2600, Canberra, ACT, Australia*
[d] *Hunter Community Environment Centre. 167 Parry St, 2303, Hamilton East, NSW, Australia*
[e] *Centre for Research on Energy and Clean Air (CREA), S¨orn¨aisten Rantatie 13 C, Helsinki, Finland*
[f] *Institute for Applied Ecology. University of Canberra. Kirinari St. Bruce, ACT, 2617, Canberra, Australia*
Email: anna.lintern@monash.edu

Abstract: In Australia, we have a significant gap in knowledge on the source and fates of mercury (Hg) in waterways. One key source of Hg is coal-fired power plants. However, the Hg can originate from different parts of the power plant – it can originate from the ash dams in power plants, or from the deposition of atmospheric emissions. It is difficult to implement appropriate management strategies without clearly identifying where in the power plant the Hg is originating. In addition, in Australia the impact of coal-fired power stations on mercury deposition in nearby waterways has not been clearly quantified.

This study therefore aims to address these two knowledge gaps using an approach that uses multiple lines of evidence. We used lake cores, extensive surface sediment sampling, hydrodynamic modelling and atmospheric modelling to (i) piece together the impact of coal-fired power stations on mercury deposition in waterways, and (ii) to identify the origin of mercury in the power stations. We used Lake Macquarie as a case study. Located in New South Wales, Australia, the Lake Macquarie catchment is a significant energy production hub in Australia, with four coal-fired power stations (historically).

Mercury analysis of the lake cores indicated that there has been an increase in Hg fluxes into Lake Macquarie at the same time as the commissioning of the coal-fired power stations in the catchment in 1956, 1963, 1967 and 1981. The cores also indicate slight decreases in Hg fluxes in ~1990 and ~2007, which coincide with the installation of emission management technologies into the power stations. These results indicate the impact that coal-fired power stations have had on Hg levels in Lake Macquarie and provides evidence of the positive impact that emission reduction technologies can have.

A hydrodynamic model, coupled with a particle density model of Lake Macquarie demonstrated the transport of particles from the ash dams of two coal-fired power stations on the shores of Lake Macquarie. The hydrodynamic transport of particulates through Lake Macquarie do not correlate with the spatial pattern of Hg concentrations in the surface sediments across Lake Macquarie. As such, it appears that the ash dams are not the key contributor of Hg that is being emitted into Lake Macquarie from the nearby coal-fired power stations. Instead, it appears that atmospheric emissions (i.e., emissions from the stacks) are the key contributor of Hg to Lake Macquarie.

These findings emphasise the critical need for managing atmospheric emissions of coal-fired power stations using technologies such as wet scrubbers to reduce Hg concentrations in nearby waterways to protect both public and ecosystem health.

Keywords: *Power plants, Hunter Valley, Bituminous coal, management, emissions*

Modelling water quality for Lake Victoria: validating lake behaviour with satellite imagery

Alicja Makarewicz[a], Jeff Newman[a], Rob Daly[a], Brooke Swaffer[a] and Leon van der Linden [a]

[a] *Catchments and Environmental Science, SA Water, Adelaide, 5000, Australia*
Email: alicja.makarewicz@sawater.com.au

Abstract: Lake Victoria is a remote water storage operated by SA Water and used to manage the delivery of water and support South Australian water entitlements. This work investigated opportunities where Lake Victoria could be used to mitigate risks from water quality events by diverting flows into the lake. A 3D hydrodynamic model was developed to evaluate lake dynamics and determine the conditions which promote dilution within the shallow waterbody. Sentinel 2 imagery was applied to validate simulated lake mixing behaviour coupled with on-ground turbidity measurements illustrating the model's ability to provide greater resolution insight into lake behaviour given its remoteness.

Lake Victoria had not been previously modelled beyond being conceptually represented within basin scale approaches. Additionally, there had been no previous assessment of the potential for the lake to mitigate adverse water quality events and what conditions are required to achieve benefits. Previous operations demonstrated that water quality benefits can often be limited, with operations significantly constrained by water security and cultural heritage requirements. To investigate the capacity of the lake to mitigate salinity, blackwater and algal bloom events the objectives of this study were to: (1) explore the potential of remote sensing/satellite data sets to improve understanding of lake behaviour and (2) to develop and simulate a 3D hydrodynamic model of the lake to investigate the conditions which promote mixing behaviour.

A year-long in-lake water quality monitoring program provided data to develop and validate a hydrodynamic model. Given the lakes remoteness and lack of long-term detailed data, satellite imagery from Sentinel 2 was used to provide additional validation and insight of horizontal mixing patterns. The work designed and simulated 144 realistic scenarios and an eight-year historical hindcast to quantify the potential influence that lake operations could exert on the quality of water released to the River Murray and through to South Australia.

The modelling suggests the lake has most value in managing small to medium sized water quality events, provided conditions favour a well-mixed lake system. Simulations showed that the mixing area of the lake increased by an average of ~5% per day, with the total mixing volume ranging between 10-100%, wind dependent. Modelled scenarios of short duration events showed that an average of 80% dilution was achievable for wind directions that drove the plume away from the outlet.

The results demonstrated that the lake does not stratify for extended periods of time and stratification tends to be weak due to strong wind driven currents. These mixing conditions do not give cyanobacteria a competitive advantage. Additionally, the shallow nature of the lake means that lake turbidity is high with high winds keeping fine sediments suspended within the lake. Therefore, the lake is unlikely to support high growth rates in summer or winter, although there are periods of time when cyanobacteria are favoured in spring and autumn (i.e., when water temperature is >18ºC and turbidity is low).

This study adds to the growing literature which shows that satellite imagery along with physics-based models with highly resolved fluid dynamics have strong value in understanding how lakes behave, and the significant variations in these behaviours between systems, as well as the ability of these models to support operational strategy and planning.

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Keywords: *Hydrodynamic modelling, water quality, satellite imagery*

A case study in the use of hydrodynamic and water quality modelling tools to support the digitisation of Environmental Impact Assessment

E. McCall[a], **Anbiah Rajan**[c], **Ala'a Ahmad Rezeq**[c], **K. Heera**[a], **K. Suara**[a], **M. Barry**[a], **K. Woodborne**[a] **and L. Bruce**[a,b]

[a] *BMT Commercial Australia, Brisbane, AUSTRALIA.*
[b] *The University of Western Australia, Perth, AUSTRALIA.*
Email: emma.mccall@bmtglobal.com

Abstract: Advancement in 3D hydrodynamic and water modelling software has allowed scientists and engineers to continue to develop complex models of environment systems used to inform Environmental Impact Assessments (EIAs). Rapid development of analytical processing tools and visualisation software has opened new opportunities in how modelling outcomes are presented to stakeholders. A recent push towards the digitisation of environmental assessments foreshadowed the need to adapt processes for sharing knowledge learnt from EIAs in a transparent and easily accessible form thus paving the way towards the concept of Digital EIAs. While the benefits of Digital EIAs for improving community engagement are widely accepted, the process presents additional challenges to upskill stakeholders in the understanding of model limitations and in the advanced digital tools required to present results from complex 3D hydrodynamic and water quality models. In this study, a capacity building methodology was developed for the Environment Abu Dhabi (EAD) to develop a fit-for-purpose hydrodynamic and water quality model of the Abu Dhabi coastal waters for use in exploring alternative options for improved environmental management.

Numerical modelling software, TUFLOW WQ combined with visualisation software QGIS provided a unique set of tools to support the training program. The capacity building workflow comprised a series of workshops, assignments and tutorials to develop advanced knowledge and understanding of the use of hydrodynamic and water quality model case studies used to access the impacts of a range of conceptualised scenarios. Workshop sessions were conducted in an interactive format to guide and inform understanding of the limitations in modelling, realistic outcomes and scenario conceptualisation. The initial sessions guided the participants through development of a series of 3D model case studies, exploring the limitations and assumptions of the software and modelling process, based on Box et al. (2009) principals that “all models are wrong, but some are useful” through to determining if a model was “good enough for this particular application”. Workshop participants were then asked to develop conceptual scenarios for the Mussafah Channel case study designed to predict environmental response to proposed solutions to long term water quality issues in the region.

A second series of workshops provided the skills needed to interrogate and view results both from direct model output and processed model results. Hands on training utilising TUFLOW FV viewer plugin with QGIS guided the participants to undertake model assessments within the areas of interest, delving into a range of methods to view results such as depth average timeseries at a point, curtain graphs, and domain maps of modelled parameters. Results for the water quality scenario modelling were presented in a range of percentile maps that could be interrogated by participants to engage, developing an understanding of results and limitations of 3D modelling of a complex coastal system. The interactive sessions enabled stakeholders to be involved in model design and conceptual scenario development and thus learn of both the usefulness and limitations of hydrodynamic and water quality models in supporting the digitisation of EIAs. Engaging stakeholders throughout the process aided in determining the key hydrodynamic and water quality processes to be modelled and scenario impact assessment. Training on the visualisation of model output was designed to further stakeholder understanding of the cause and effect pathways and impacts of alternative mitigation measures for water quality improvement and thus enrich the Digital EIA process.

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Keywords: *Environmental modelling, TUFLOW FV, QGIS, stakeholder engagement*

EXTENDED ABSTRACT ONLY

An empirically driven model of water mass balance and nutrient loads in Lake Tuggeranong

R. Ubrihien and **F. Dyer**

[a] *Centre for Applied Water Science, University of Canberra*
Email: rod.ubrihien@canberra.edu,au

Abstract: Lake Tuggeranong is a man-made lake in the south of Canberra. The lake has had persistent problems with cyanobacteria blooms. The lake has been closed for approximately one hundred days each year this century because of the risks associated with these cyanobacteria blooms. There is an imperative to reduce the impact of these blooms which requires an understanding of the physical, chemical and biological processes occurring in the lake.

Three years of data were collected on the discharge to and from the lake as well as nutrient concentrations at the inflows to the lake. These data were used to develop empirical mass balance models of lake hydrology and the nutrient loads in the lake. The lake has three main inputs form predominantly urbanised catchments. Theoretical discharge models and stream height gauges were available to calculate the discharge to the lake from two of the inflows, the third major inflow was not able to be measured and needed to be approximated. Multiple methods were used to approximate this third major inflow. The hydrological data from the different methods were used in conjunction with lake volume and evaporation data to produce a water mass balance model, providing an indication of accuracy of the different methods. The different modelling methods produced varying outcomes which were used to approximate error in the model. Nutrient concentrations measured at the lake in baseflow and event conditions were used to approximate external loading to the lake.

Within the lake nutrient concentrations and forms as well as temperature and dissolved oxygen data were collected down depth profiles in the lake. This allowed an understanding of the onset and duration of thermal stratification in the lake and the response of nutrients to changes in stratification. Internal nutrient loading for the stratified period was approximated. From these data empirical based models have been developed that provide an indication of the relative importance of internal and eternal loading in the lake.

The modelling of the external and internal loading to the lake along with the collection of regular phytoplankton samples have provided an understanding of the processes leading to algal blooms. Nutrient loads in the lake are dominated by external nutrient inputs. The biological response seen in the phytoplankton community also demonstrates that external nutrient loads are required to support cyanobacteria bloom. This was evidenced seen through the extreme conditions that occurred in the summer of 2019/20.

Keywords: *Lake, Mass balance, nutrients, cyanobacteria*

Modelling purified recycled water inputs to Lake Wivenhoe, Queensland, Australia

Songyan Yu [a], **David P. Hamilton** [a], **Badin Gibbes** [b], **Tony Weber** [c], **Marieke Frassl** [a], **Katrin Sturm** [d, b] **and Cameron Veal** [d, a]

[a] *Australian Rivers Institute and School of Environment and Science, Griffith University, Nathan, 4111, Australia.* [b] *School of Civil Engineering School of Civil Engineering, The University of Queensland, St Lucia, 4072, Australia.* [c] *Alluvium Consulting, Brisbane, 4006, Australia.* [d] *Seqwater, Ipswich, 4305, Australia*
Email: sunny.yu@griffith.edu.au

Abstract: The Western Corridor Recycled Water Scheme (WCRWS) is part of Seqwater's drought response plan. It is designed to supplement existing drinking water supplies by producing Purified Recycled Water (PRW) that will provide up to 20% of the existing demand from the Seqwater Water Grid. The WCRWS will commence re-mobilisation to full operational production to deliver PRW through Logan's Inlet into Lake Wivenhoe, the major drinking water storage for South-east Queensland, within two years of when the region's combined key bulk water storages fall below 60% capacity. Our study focussed on better understanding the barrier effect of Lake Wivenhoe in diluting PRW. We undertook a modelling study to inform and assess whether Lake Wivenhoe is an effective barrier that can help to manage public health risk from a highly unlikely scenario that includes multi-barrier treatment failure resulting in pathogens being introduced through PRW into the Lake.

We used catchment model outputs of discharge and pathogen loads as inputs to a lake model to simulate the fate and transport of PRW and pathogens in Lake Wivenhoe. The simulations assumed a hypothetical, highly unlikely, multi-barrier failure in the Purified Recycled Water Treatment Plant that would allow pathogens to enter the PRW and the Lake. The simulations were conducted under a suite of scenarios that involved different water levels (30% and 50% of Full Supply Level (FSL)), PRW inflows (70 ML/d, 160 ML/d, and 180 ML/d), and upstream dam (Splityard Creek (SYC) hydro-power dam) operations (operating continuously and turned off). Five representative pathogens were considered in this study, including *Campylobacter* (the representative pathogen for all bacteria), *Cryptosporidium* (for all protozoa), adenovirus (for all viruses), *E. coli*, and enterococci (collectively, faecal coliform bacteria). The simulated PRW and pathogen concentrations were reported for eight sites of interest in the Lake, including two Water Treatment Plant offtake sites, five recreational sites, and one mid-lake monitoring site.

Simulated PRW concentrations varied among the eight reporting sites but showed a consistent pattern across the scenarios. In one scenario (PRW inflow of 180 ML/d, initial water level of 30% FSL, and SYC continuously operating), the simulated PRW concentration was 70% of the volume in Logan's Inlet within 15 days, increased subsequently to 90%. Pelican Island followed a similar pattern but with lower PRW concentrations. PRW concentration at the Esk Offtake site was extremely low throughout the simulation. A PRW plume formed away from the inflow to Logan's Inlet but remained mainly constrained to the Inlet area. Pathogen inputs from the catchment dominated the concentrations in Lake Wivenhoe even with a simulated highly unlikely, multi-barrier failure, no matter the volume of the simulated PRW or lake water levels. The maximum pathogen concentrations at all eight selected locations within the Lake usually occurred some days after major rainfall events in the catchment and were not related to the timing of PRW input, suggesting that these pathogens theoretically introduced through PRW were mostly contained within Logan's Inlet area.

This study concludes that Lake Wivenhoe is a natural barrier that dilutes PRW and prevents pathogen contamination of drinking water. The catchment derived inputs constituted the most significant simulated pathogen loads in the model. The maximum pathogen concentrations at all eight selected locations within the Lake usually occurred some days after major rainfall events in the catchment and were not related to the timing of PRW input. It highlights that PRW input into Lake Wivenhoe represents a very low level of risk in terms of pathogens for water offtakes from the Lake under a range of different climate and operating conditions related to water levels and PRW volumes.

Keywords: *Drinking water, reservoir, water safety and security, drought response, water management*

Relative importance of hydrology optimization targets and sediment routine combinations towards calibration of a global sediment model

Conrad Brendel [a], **Alena Bartosova** [a], **and Charlotta Pers** [a]

[a] *Swedish Meteorological and Hydrological Institute, Norrköping, Sweden*
Email: conrad.brendel@smhi.se

Abstract: Modeling of global sediment fluxes can offer valuable insights to past and future trends in response to environmental and anthropogenic changes; however, the development and calibration of large-scale sediment models presents many challenges. The World-Wide Hydrological Predictions for the Environment (HYPE) model, is a physically-based, semi-distributed hydrology model which has been used to simulate suspended sediments at a daily time step at the global scale (Arheimer et al., 2020; Bartosova et al., 2021). Challenges associated with large-scale models include their reliance on quality discharge simulations in order to accurately simulate suspended sediment concentrations, and that the subjective choice of which modeling routines are used may limit model performance. Thus, the goal of this study was to use a case study model to assess the relative importance of three factors on the performance of suspended sediment simulations in World-Wide HYPE: 1) the optimization target of the starting hydrology model parameter set, 2) the chosen stream sedimentation/resuspension method, and 3) the method used apply seasonal erosion corrections.

For this study, we selected a HYPE model of the Devoll river in southern Albania. The Devoll river region is characterized by active erosion processes which cause high sediment loading in the river. Two hydropower reservoirs have recently been constructed along the river; thus, there is a particular interest in modeling the flux of suspended sediment and its implications for reservoir sedimentation. The case study model was constructed by first extracting a submodel of the area from the World-Wide HYPE model and then refining the catchment delineations. In total, the case study model was divided into 39 subbasins with a median size of 56.12 km^2. A wealth of local data was available for model calibration and validation, including multi-decadal daily discharge and suspended sediment timeseries.

To assess the importance of the optimization targets of the calibrated hydrology model and the combination of selected sediment routines on the performance on simulated suspended sediment concentrations, the case study model was calibrated using an ensemble of 18 model setups. This ensemble represents the unique combinations of three hydrology model optimization targets (discharge, actual evapotranspiration, and potential evapotranspiration), two sedimentation/resuspension methods (redistribution according to flow and simplified Bagnold equation), and three seasonal erosion correction methods (no adjustment, values from earth observation indices, and calibrated values). Upon completion of model calibration, a matrix of model fit statistics for the 18-model ensemble was created to assess the impact of the factors on discharge, evapotranspiration, and sediment simulation performance.

Understanding the importance of hydrology optimization targets and sediment routine combinations on the calibration of suspended sediments will provide valuable insight to inform and optimize the construction and calibration of large-scale sediment flux models. Results from the study will be used to guide future development of the HYPE model and to improve the simulation of sediment fluxes at the global scale.

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Keywords: *Suspended sediments, large-scale modeling, model calibration, hydrology*

EXTENDED ABSTRACT ONLY

Suspended sediment load estimation in an ungauged catchment: applying SedNet below the regional scale

A.J. Gibson[a] and **G.R. Hancock**[a]

[a] *School of Environmental and Life Sciences, University of Newcastle, Callaghan, 2308, Australia*
Email: abraham.gibson@newcastle.edu.au

Abstract: Soil erosion and elevated sediment loads associated with agricultural activity have caused significant environmental issues across Australia. Targeted management and sediment control are seen as the most efficient and effective strategies to reduce the impact on waterways. However, this requires catchment specific data. This is difficult in data poor catchments, with model methods available to overcome this. This study independently calibrated and then applied the SedNet model to estimate a sediment budget for a 575 km^2, ungauged, agricultural catchment of south-eastern Australia. The independent calibration consisted of using remote sensing data, field measured soil parameters, along with gridded runoff products to create a specific dataset for the application of the model below the regional scale. Model estimates were then compared with field data to assess soil loss and redistribution across the catchment.

From 1975 to 2015, SedNet estimated average suspended sediment concentrations between 70 and 120 mg/L. Monitoring data collected from 2014 to 2016 showed suspended sediment concentrations between 30 and 350 mg/L, comparable with the model estimates. The field data indicated that soil loss and redistribution across the catchment is low, however the sediments loads are elevated enough to still be impacting river health. Overall, SedNet accurately represented current catchment and river conditions and provided a reliable estimation of sediment yield, demonstrating the ability to estimate sediment loss and redistribution across data poor catchments using a multifaceted modelling approach. Methodologies, such as these offer the ability to better assess the impacts of erosion on sediment loads to develop strategies to effectively manage excess suspended sediment.

Keywords: *SedNet, river health, sediment budget, water quality, soil erosion*

Using a numerical Landscape Evolution Model to assess long term erosional stability of tailings dams

Greg Hancock [a], **Tom Coulthard** [b] **and Dimuth Welivitiya** [a]

[a] *School of Environmental and Life Sciences, The University of Newcastle, Callaghan, Australia, 2308*
[a] *School of Environmental Sciences, University of Hull, Hull, UK*
Email: greg.hancock@newcastle.edu.au

Abstract: Tailings are a by-product of the processing of minerals. Tailings are usually fine grained, contain water and can containing processing chemical residues and are usually very erodible. Tailings are commonly stored in 'tailings dams' and these dams are a feature of many mine sites. Tailings dams are considered to have similar risk to that of water storage dams with geotechnical, seismic, hydrological (rainfall) and erosional induced failure concerns. A further risk is the potential release of polluted water and the accompanying chemicals and fines, which if released can travel large distances downstream. In the majority of mines, tailings dams will be permanent geomorphological features. However, every dam has a design life and some have suggested that closure designs be considered for a 1000 year design life with others consider 10 000 year scenarios.

New methods for assessing long-term behaviour of tailings dams including numerical modelling are needed. Previous work using computer based Landscape Evolution Models (LEMs) has examined tailings dam design using both experimental landscapes and proposed designs using the SIBERIA LEM (Hancock, 2021). This work demonstrated that management of water, and, in particular, concentrated flow was extremely important. LEMs provide information on erosion rates, type of erosion and where erosion is likely to occur. They can therefore provide guidance on long-term behaviour, which allow designs to be tested and improved accordingly. The design, construction and long-term management of tailings dams is an issue that has and will exist for most mines. This work (1) demonstrates the use of LEMs in particular, the CAESAR-Lisflood model (Coulthard et al., 2013) as a tool to better understand the long-term erosional stability of tailings dams and (2) provide a means of assessing downstream geomorphic and water quality impacts of tailings dam failure.

CAESAR-Lisflood models the entire catchment which includes both the natural hillslope as well as the tailings. Sediment output for the modelled domain is a combination of both the natural hillslope material, material from the failed embankment and the tailings. CAESAR-Lisflood also models the transport of all size fractions. However, with tailings it is the fine fraction that is the most easily mobilised and transported. The findings demonstrate that post dam wall breach water quality will be reduced for centuries and may never reach background (pre breach) levels given the amount of tailings stored in the dam. This presents a permanent change in water quality with sedimentological and ecological concerns downstream of the site.

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Keywords: *Tailings dam, water quality, landscape evolution model, soil erosion, CAESAR-Lisflood, dam failure*

Use of high-resolution DEM for improving stream slope estimates and its effect on modelled fine sediment loads

A. Pollett[1] and B. Fentie[2]

[1] *Queensland Department of Resources, Nambour,*
[2] *Queensland Department of Environment and Science, Dutton Park*
Email: angela.pollett@resources.qld.gov.au

Abstract: Stream slope is used in Great Barrier Reef (GBR) catchment models with the estimation of mean annual streambank erosion. Streambank erosion is the dominant erosion process in a number of GBR basins. Over low-relief terrain detailed high-resolution digital elevation model (DEM) data is required to resolve the subtle slopes and small landscape features such as levee banks and minor channels. Current stream slope estimates use a relatively coarse (30m) resolution DEM. To improve the accuracy of slope estimates, a semi-automatic method has been developed to make use of available high-resolution (1m) LiDAR DEM data.

The revised slope estimates were implemented in the Burnett-Mary Region catchment model to evaluate their impact on modelled fine sediment supply from streambank erosion. These changes in stream slope resulted in a 16% reduction in modelled streambank erosion supply of fine sediment. The use of high-resolution LiDAR DEM provided a superior level of accuracy, detail and confidence for stream slope calculation when compared to the use of low-resolution DEM data, particularly over short stream reaches and low-relief landscapes. Where available, finer-resolution topographic data such as LiDAR can be used to improve model parameterisation and increase confidence in the modelling of sediment from streambank erosion.

Keywords: *Stream slope, streambank erosion, LiDAR, DEM, Great Barrier Reef*

Assessing performance of the MERGE model for simulating gully interventions

M. J. Prentice [a], M. W. Waud [b], D. P. Hamilton [a], and M. E. Roberts [ac]

[a]Australian Rivers Institute, Griffith University, 170 Kessels Road, Nathan, Queensland 4111, Australia
[b]Healthy Land and Water, Brisbane City, Queensland 4000, Australia
[c]School of Environment and Science, Griffith University, Queensland 4111, Australia
Email: m.prentice@griffith.edu.au

Abstract: Gully erosion is a significant safety, economic, and environmental issue which affects agricultural productivity, infrastructure stability, and water quality of receiving waters. Hot spots of gully erosion have been identified across every continent and control and mitigation methods are sought. Despite a variety of interventions available to prevent gully formation and to rehabilitate existing gullies, cost-effective interventions need to be tailored for each gully. MERGE (modelling erosion resistance for gully erosion) is a one-dimensional process-based model for gully erosion, designed to simulate erosion events in classical gullies and quantify the benefit of interventions in silico. Simulations are used to inform the appropriateness of interventions applied in situ. The aim of this study was to assess the performance of MERGE at assessing the benefits of three commonly applied gully treatment interventions using on-ground input data.

The model was run under steady state conditions with input data specific to Fernvale Gully in the Lower Brisbane River Catchment, South-East Queensland, Australia. Interventions simulated included; reducing the flow (Q) at the gully head (as a result of catchment works), increasing vegetation cover of the gully channel, and rock-capping of the gully head. Interventions relating to reducing Q and increasing vegetation cover were carried out for 'small','medium', 'large', and 'very-large' modifications to Q and Manning's roughness (n), respectively. The intervention relating to rock-capping was carried out by assuming no erosion in the gully head. Interventions were also simulated for combinations of 'small' reduction in Q, 'small' reduction in vegetation cover, and rock-capping. For each intervention, erosion resistance (J)—being a largely unknown quantity in the scientific literature—was input as a selection of values ranging between high and low erodibility.

MERGE was demonstrated to be a useful tool to guide on-ground decision making for gully management interventions. Specifically, the simulations provide insight into the relative benefits of each intervention on-ground at Fernvale Gully. MERGE demonstrated that each gully intervention performed markedly differently depending on antecedent gully conditions. MERGE also demonstrated that reducing Q resulted in a proportional linear reduction in sediment flux (QC) exiting the gully, whereas increasing vegetation cover resulted in a non-linear reduction in QC, with ever increasing vegetation cover producing reduced returns. The benefit of combining interventions was not additive, illustrating the benefit of MERGE for assessing potential outcomes when more than one intervention is to be implemented.

The implementation of MERGE in this study allowed the most effective intervention strategies to be identified on-ground for the gully of interest, thus demonstrating the potential of MERGE to guide decision making for gully management. Therefore, future application of MERGE might look to apply scenarios to help inform the most appropriate interventions across a suite of gullies. Such an assessment might entail gullies with complex morphology (i.e., dendritically shaped, and multiple heads), and a broader scope of interventions than considered here (e.g., porous check dams, and the application of gypsum and fertilisers).

Keywords: *Erosion, gullies, intervention, process-based model, sediment*

Calibration of a point scale model to the RUSLE

Dan Rattray [a]

[a] *Horizon Soil Science and Engineering, Toowoomba , Queensland, Australia*
Email: dan.rattray@horizonsoil.com.au

Abstract: A simulation methodology was required to assess potential water quality impacts of a proposed irrigation scheme. Current land use of the proposed irrigation development was grazing which had been modelled in the Source framework using a Revised Universal Soil Loss Equation (RUSLE). Our challenge was to calibrate the Howleaky model to the baseline conditions for hillslope erosion against estimates from the Source model and apply Howleaky to a wider range of irrigated crop.

Dougall et al (2014) described processes used in the Great Barrier Reef's Source Catchment model (Source) for the Burdekin catchment. Water quality models used within Source vary for each land use and water quality constituent. Cropping areas are modelled using daily time step models (APSIM and HowLeaky) that consider farming system processes and landscape characteristics including soil types. Erosion in grazing is modelled using a RUSLE that includes a 3 monthly time series of groundcover derived from satellite imagery. The aim was to build on Howleaky's ability to estimate hydrology and water quality based on temporal variation in soil cover derived from satellite imagery and to cross check its estimates with the current RUSLE approach.

The HowLeaky model (Queensland Government, 2019) simulates water dynamics between vegetation and soil management at the paddock scale. Main inputs include: weather (http://www.longpaddock.qld.gov.au/silo/); soil; crop; pasture and fallow management parameters and parameters describing irrigation, nitrogen, phosphorus and pesticide inputs. Soil descriptions were obtained from land resource assessments and parametrisation methods outlined in Chamberlain et al. (2020). Erodibility K and LS factors were taken from Source model data.

A dynamic pasture description derived in HowLeaky based on pasture growth in response to rainfall was calibrated against the 3 monthly cover data from Source. HowLeaky parameters adjusted included: maximum leaf area index to reflect maximum observed cover; residue decay rate; and Radiation Use Efficiency. Soil cover estimates from the dynamic Howleaky model and satellite imagery were well aligned while erosion estimates from Howleaky and the RUSLE compared well (near 1:1 relationship and R^2 of 0.98).

The calibrated Howleaky model was then applied with greater confidence to estimated erosion rates under a range of crops and irrigation practices. This approach to estimating paddock scale erosion can be integrated into the Source catchment model framework to estimate impacts of proposed land use change and irrigation on end of catchment water quality outcomes.

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Keywords: *RUSLE, HowLeaky, erosion, water quality, irrigation*

Application of a coupled soilscape-landform evolution model in assessing erosional stability of a post mining landform

W. D. Dimuth P. Welivitiya and Greg R Hancock

[a] *College of Engineering, Science and Environment, The University of Newcastle, Callaghan, NSW 2308, Australia.*
Email: wdw334@newcastle.edu.au

Abstract: For post mining landscapes there is a universal requirement for sustainable mine rehabilitation. This means ensuring the erosional stability of post-mining landform. Post mining landforms consist of unconsolidated waste which can be highly erodible. In such structures of loosely bonded material, rill erosion and gully erosion are major issues which leads to degradation of the landform. To ensure long term stability and sustainability, these landforms need to be designed to minimize rilling and gulling.

Over the years various landform evolution models (LEM) have been used to predict the evolution of such landforms and identify areas prone for gully erosion. Although these endeavors have met with good success, the majority of models do not account for changes in surface properties (particle size distribution) of these structures during their evolution.

Here we demonstrate the capabilities of the State Space Soil Production and Assessment Model (SSSPAM) in simulating gully erosion on a post-mining landform. SSSPAM is a coupled landform-soilscape evolution model capable of simulating fluvial erosion and armouring, diffusive erosion (surface), sediment deposition, and weathering within the soil profile. SSSPAM was specifically developed to incorporate the evolution of the soil profile in combination with landform evolution. For this reason it is more suitable for simulating unconsolidated structures such as post-mining landforms.

Simulations were done using a digital elevation model (DEM) derived from LIDAR survey of a working coal mine waste rock dump to represent the approximate initial landform. Site specific SSSPAM parameter calibration was done using runoff-erosion data derived from flume experiments. Calibrated model parameters together with the approximated initial landform DEM and the rainfall record form a nearby weather station was used to simulate the initiation, growth and stabilization of gullies at two different sites in the waste rock dump. The results show that SSSPAM is able to predict the position and general geomorphic characteristics of the gullies observed on the landform. Further, the results demonstrate how the surface properties (particle size distribution) change over time due to the process of armouring which is known to reduce the rates of erosion. In addition to the results presented here SSSPAM can also be used to investigate the impact of various factors influencing post-mining landform evolution such as land surface properties (particle size distribution), climate variability, weathering of material and vegetation cover.

Keywords: *Mine rehabilitation, SSSPAM, pedogenesis, weathering, armouring, LEM, gullying*

EXTENDED ABSTRACT ONLY

Setting tolerable soil erosion and vegetation cover targets across New South Wales

Xihua Yang [a], **John Leys** [b,c], **Jonathan Gray** [a] **and Mingxi Zhang** [d]

[a] NSW Department of Planning, Industry and Environment, Parramatta, NSW 2150, Australia
[b] Fenner School of Environment and Society, Australian National University, Canberra, Australia
[c] Land and Water – Black Mountain, CSIRO, Canberra, Australia
[d] School of Molecular and Life Sciences, Curtin University, Bentley, Western Australia, 6102
Email: xihua.yang@environment.nsw.gov.au

Abstract: Hillslope erosion is the dominant form of erosion in Australia and many parts of the world. 'Tolerable' hillslope erosion or tolerable soil loss (TSL) targets needs to be established considering the inherent physical capacity of the land to sustain specific land uses and management practices without degradation to soil, land, air and water resources. The existing methods on TSL estimation vary greatly over different regions and applications, and few practical and dynamic methods are available. In this study, we explored a dynamic approach to set TSL and vegetation cover targets across the state of New South Wales (NSW), Australia considering the prevailing hillslope erosion and the sustainable erosion level. Over 20-year fractional vegetation cover and rainfall erosivity time-series have been used to determine the hillslope erosion and the TSL targets monthly and the 50th percentile was set as the target. Consequently, the monthly vegetation cover levels have been set to sustain the TSL targets on a pixel-by-pixel (100 m) basis. We further assessed the TSL targets against the land and soil capability classes and their spatial and temporal variation across NSW Local Land Services regions. The findings help to identify the locations and times with hillslope erosion exceeding a tolerable threshold value across NSW. This approach is practical, semi-quantitative and portable as the input datasets are widely available, thus providing a useful tool to determine varying TSL values for sustainable soil and land management at any location and period.

Keywords: *Hillslope erosion, tolerable soil loss, vegetation cover, rainfall erosivity, land and soil capability*

The dial-a-ride problem in the case of a patient transportation system in Brazil

M. Bernardo [a], **A. L. Souza** [b], **M. Amirghasemi** [a], **J. Barthelemy** [a] **and P. Perez** [a]

[a]*SMART Infrastructure Facility, University of Wollongong, Northfields Avenue, 2522 Wollongong, Australia*
[b]*Departamento de Computação, Universidade Federal de Ouro Preto, 35400000 Ouro Preto, Brazil*

Email: marcella@uow.edu.au

Abstract: Despite its importance, the role played by logistics is often overlooked in health care. Patients often need to be transported to medical facilities and treatment units. In Brazil, the transportation department of municipal health care systems need to provide transport to patients from small municipalities to public hospitals located in large cities, as some medical services are only provided in these hospitals. The problem of transporting patients can be modelled as a Dial-a-Ride Problem (DARP). The DARP is a variant of the Vehicle Routing Problem (VRP) where a transportation request includes both a pick-up and drop-off locations and not only time window constraints but also other users' constraints are considered. The general goal of DARP is to calculate a route plan to meet a set of transportation requests by using a given fleet of vehicles at minimum cost.

In this paper, we aim at solving the DARP arising in the daily operation of the transportation sector of the municipal health care system in Ouro Preto, Brazil. Every day, the transportation department transfers patients from their pick-up location, which is either the patient's home or a collective point, to public hospitals located in the capital Belo Horizonte. Whether a patient is collected from their home or a public location (collective point) depends on the patient's condition. Patient transportation requests also differ regards to patient's vehicle requirement. That is, a transportation request can include either a single patient or a patient and a companion person and based on the patient's need (e.g. in a wheelchair) a specific vehicle might need to be allocated to the patient. To provide the transportation service, the sector leases a fleet of heterogeneous vehicles. The vehicles have different (leasing) costs and load capacities. The main difference between the problem faced by the Ouro Preto's health care system and DARPs from the literature is that the proposed problem must have no transportation request rejected. That is, all patients must be served.

To solve this problem, we introduce a variable neighbourhood search (VNS)-based metaheuristic. The VNS method counts with a greedy method to find an initial solution and a randomised variable neighbourhood descent (RVND) method as the local search procedure. Solutions are evaluated using a cost function which includes routing cost and penalty cost for violating time window constraints. The VNS shaking procedure includes six inter-route operators, whereas the RVND method includes three. We calibrate the parameters of the VNS, namely neighbourhood combination, penalty for time window constraint violation, and stopping criteria, using a well-known calibration tool, the *iRace* package. We validate the performance of the proposed VNS on benchmark instances from Parragh (2011). We also create different test problems based on data provided by the public health care system and test the proposed approach on them. The computational experiments on Parragh (2011)'s instances show that our VNS is able to find optimal solutions in short computational times. When VNS was not able to find the optimal solution, the gap was less than 2.95%. The results on the designed test problems indicate that by using the proposed approach, the transportation sector can lease fewer vehicles than it has been currently renting to attend daily patient transportation requests. We can conclude that the VNS metaheuristic is an efficient tool for the municipal health care transportation sector to improve routing and vehicle costs.

Keywords: *Dial-a-ride problem, vehicle routing problem, patient transportation, variable neighbourhood search, randomised variable neighbourhood descent, optimisation*

Freight train scheduling via decentralised multi-agent deep reinforcement learning

A. M. C. Bretas [a], **A. Mendes** [a], **S. Chalup** [a], **M. Jackson** [b], **R. Clement** [b] **and C. Sanhueza** [b]

[a]*The University of Newcastle, New South Wales, Australia*
[b]*Hunter Valley Coal Chain Coordinator, Broadmeadow, NSW, Australia*
Email: c3308652@uon.edu.au

Abstract: Rail traffic planning and scheduling problems have been challenging academy and industry for a few decades. Specifically, problems in the short term and real-time horizons deal with simultaneous decision-making of trains, stations and terminals. Approaches focused on decentralised decision-making have been successful in delivering real-world committed solutions. This work focuses on decentralised real-time decision-making in a closed freight rail network and applies multi-agent deep reinforcement learning (MADRL) to find efficient timetables.

We apply the MADRL model to solve the traffic decisions arising in the Hunter Valley Coal Chain (HVCC) in New South Wales, Australia. The approach uses the same simulation model currently in use for capacity planning of the system, thus allowing tests with real data. The environment is modelled as a decentralised, partially observed Markov decision process (dec-POMDP), where the train, load point, and dump station agents decide upon train movements based on local observations. The observations follow a novel state encoding strategy for rail traffic management composed of nine layers. We benefit from this strategy to apply a decentralised execution with a centralised learning approach through proximal policy optimisation.

The experiments revealed a significant performance improvement for the ten instances tested, which reproduce the challenges faced in the HVCC operations. The approach is suitable for varied levels of rail network complexity, generating efficient solutions without scaling issues. The MADRL outperformed the heuristic in use by HVCC's simulation model and a high-performance genetic algorithm in all instances, reaching performance improvements of up to 72.00% and 47.42%, respectively. Therefore, the framework with the MADRL and the simulation model allows its application with real world instances in an efficient and reliable way. These results show the method's consistency and draw a safe path towards a decentralised rail traffic management system.

Keywords: *Multi-agent deep reinforcement learning, simulation-based machine learning, decision-making, rail traffic management, train scheduling*

The Standard Refuelling Facility Expansion Problem: A Case Study in Australia

Juan Calle[a], Roberto Perez-Franco[a], Vicky Mak-Hau[b], Danilo Abril[c] and Daniel Rojas[d]

[a]*Centre for Supply Chain and Logistics, Deakin University, Burwood, Vic 3125, Australia*
[b]*School of Information Technology, Deakin University, Burwood, Vic 3125, Australia*
[c]*Independent Researcher, Colombia*
[d]*EIA University, Colombia*
Email: jcallesalazar@deakin.edu.au

Abstract: Refuelling facilities are critical infrastructure for road freight transport networks, since every vehicle must refuel in order to move freight. Recent advances in alternative fuel (alt-fuel) vehicles have made the location of refuelling facilities even more critical, since the driving range of alt-fuel vehicles is less than for traditional fuel-powered vehicles (Deb et al., 2018). Transport companies have decided to establish their own refuelling facilities in order to guarantee the feasibility of their vehicles' movements, as well as to optimise the refuelling process. This article presents a methodology to assist transport companies to locate their own refuelling facilities. It first proposes a methodology to convert GPS data into trips to understand where the vehicles are moving, then uses this information as an input for a customised Mixed Integer Programming (MIP) model that suggests potential locations for refuelling facilities. The methodology is applied to a case study in Australia (the Melbourne-Sydney corridor).

The transport company that is the subject of this case study provided all the required data to run the model[1]. Their motivation to do the analysis in this corridor was the high amount of fuel refuelled at retailers (refuelling facilities of third parties), which is in the order of tens of millions of litres of fuel per year. They decided to investigate the movements of the fleet to evaluate the business viability to locate their own-refuelling facilities in the corridor. The main advantage for the transport company to have their own-refuelling facilities was to enable the purchase of fuel at wholesale prices directly from fuel suppliers, thus improving the efficiency of refuelling operations, since strategically located refuelling facilities could mean that the vehicles spend less time in the refuelling operation.

For this particular case study, the model suggests that only by improving the refuelling decision taken by the fleet (where and how much to refuel) 2.3% of savings (representing hundreds of thousands of dollars) could be obtained out of the total refuelling cost of the company in the analysed corridor. After doing a sensitivity analysis on the fuel consumed in the corridor, it is suggested that only one own-refuelling facility should be located, since the location of two refuelling facilities would not be an optimal solution if the fuel consumed in the corridor is reduced by more than 20%.

The MIP presented in this article is a contribution to the flow refuelling location literature, since it adds differential prices of the fuel in each refuelling facility as a driver to locate refuelling facilities. Another contribution is the novel procedure presented in this paper to process and convert large amounts of GPS data into trips.

[1] All data referring to the company has been masked to protect its confidentiality

Keywords: *Transport, flow refuelling location, GPS data transformation, mixed integer programming*

Tactical network planning for parcel delivery companies

Saman Eskandarzadeh and **Behnam Fahimnia**

Institute of Transport and Logistics Studies, University of Sydney Business School, Australia
Emails: saman.eskandarzadeh@sydney.edu.au, ben.fahimnia@sydney.edu.au

Abstract: Network operations reside at the heart of postal companies. The small profit margins of the postal companies and the growing demand for faster and cheaper services require effective planning and exploring any opportunity to improve services while reducing the costs. Postal companies often rely on economies of scale to reduce cost. However, full exploitation of economies of scale which is achieved by consolidation of parcels at sortation facilities leads to more sortation activities and higher sortation cost. On the other hand, less exploitation of economies of scale leads to less utilization of capacity and higher transport cost. We investigate an important interplay in network planning between sortation activities and transport activities for postal companies that heavily rely on small-size containers for parcel transportation.

The problem considered here falls into the class of service network design problems (Guastaroba, Speranza, and Vigo 2016; Wieberneit 2008; Crainic 2000) as well as general network design problems (Crainic 2000). Service network design problems have three main goals: (a) which transport services are offered over the transportation network, (b) how the freight or parcel traffic is routed using the services, and (c) which policies and operations to apply on the passing traffic at nodes of the service network. These policies could include policies for consolidation of freight or parcels at intermediate nodes en-route to their destinations or policies for allocation of traffic across nodes of the network.

We present a MIP-based methodology to model and analyse this problem incorporating a specific set of sortation decisions that arise from using small-containers. We use real data from a major postal company in Australia to calibrate our model and generate insights.

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Keywords: *Mixed-integer programming, service network design, tactical planning*

Hydrogen bus route planning in regional Victoria

R. Esmaeilbeigi [a] **V. Mak-Hau** [a] **G. Pineda-Villavicencio** [a] **and J. Ugon** [a]

[a] *School of Information Technology, Deakin University, Geelong, VIC 3218, Australia*

Email: r.esmaeilbeigi@deakin.edu.au

Abstract: In this paper, we present a case study to optimise refuelling logistics for a hydrogen bus network in regional Victoria, Australia. The bus network under study is operated by a company that aims at introducing a new fleet of hydrogen buses. We use integer linear programming to design a decision support system that could guide the company to determine the optimal configuration of a hydrogen refuelling network. Hydrogen bus refuel speed is governed by the pressure of the refuelling pumps. A high-pressure refuel pump is more costly but has a faster refuel time, whereas a low-pressure pump is relatively more economical, but it has a longer refuel time. Higher pressure storage also allows larger volumes of hydrogen to be stored at refuel points, potentially lowering the bulk refilling frequency. As with the refuelling speed, higher pressure storage vessels cost significantly more than standard pressure storage vessels. So there is a trade-off between investing in expensive high-pressure refuel equipment so buses can be refuelled in the shortest practicable time, and in lower-cost and low-pressure refuel equipment resulting in longer refuel times. Furthermore, four replenishment activities (i.e., refuelling, exterior cleaning, internal cleaning, and potentially COVID-19 cleaning) need to be scheduled for each bus. Results of our case study show that it is possible to satisfy the total demand using one low-pressure refuelling pump. In addition, we showed that without our proposed decision support tool, the company would use 9.1% more vehicles compared to the optimal number of buses.

Keywords: *Bus scheduling, clean transport, decision support system, logic-based Benders decomposition*

Assessing last mile delivery strategies – A hybrid solution approach

Juan E. Muriel[a], **Lele Zhang**[b], **Jan C. Fransoo**[c] **and Roberto Perez-Franco**[d]

[a] *School of Engineering and the Built Environment (SEBE), Deakin University, Geelong, Victoria 3216, Australia*
[b] *School of Mathematics and Statistics, The University of Melbourne, Parkville, Victoria 3010, Australia*
[c] *Tilburg School of Economics and Management, Tilburg University, 5000 LE Tilburg, Netherlands*
[d] *Centre for Supply Chain and Logistics, Deakin University, Geelong, Victoria 3216, Australia*
Email: jmuriel@deakin.edu.au

Abstract: Urban freight is growing faster than other transport activities, and its adverse effects bring consequences to people, the environment and the liveability of cities. Although understanding its dynamics has become a priority for governments, the multiplicity of actors with conflicting objectives makes it a significant urban planning challenge. This paper develops a hybrid (simulation-optimisation) methodology to evaluate the impact of different last mile delivery strategies over the network traffic flow. The model is focused on the use of one type of on-street parking infrastructure: the loading zone (LZ). We refer to on-street LZs as parking areas that occupy space directly on the road lane. The design and management of parking systems, especially on-street LZs, is considered one of the most powerful traffic control measures with a substantial influence on the efficiency of the urban freight system. The methodology considers the decision-making process made by the road users, their interaction, and the variability of stochastic parameters (traffic conditions, competition, cruising, and illegal parking). The framework combines a stochastic cellular automata (CA) traffic microsimulation, with a metaheuristic and a commercial solver. The CA model has two layers, the lower layer describes the road network, its entry and exit points, LZ locations, traffic demand, speed limits, intersections, and traffic light settings. The upper layer manages the agents (private vehicles (PV) and delivery vehicles (DV)), their size, speed, motion, lane changing, vehicle routes, illegal parking decisions and the duration of the delivery stops. To optimise the routes of DVs, we use a greedy randomised adaptive search procedure – GRASP to solve a two-level (trucking and walking) optimisation problem and the CPLEX optimiser to re-optimise mid-route decisions. The model was developed in the Java programming language.

The methodology is applied to a CBD network simulating realistic conditions and evaluate three urban logistics strategies: *Alternative LZ, Illegal Parking and Last Delivery*. Although the results conclude that to minimise the impact of DVs the best strategy is *Illegal Parking*, important considerations need to be addressed. For instance, the location of the LZs in the study network were equally spread over an edge, with two illegal parking areas. This aspect certainly limited the well-known congestion consequences of illegal parking. For example, LZs that are located close to up- or down-stream intersections with more illegal parking will certainly spread the congestion shockwave to adjacent edges, attaining different results. A similar situation occurs when delivery vehicles parked illegally are blocking the access to buildings, side streets or public transport.

The fact that the *Illegal Parking* strategy derived better results in this study may seem counterintuitive and is likely to be controversial. However, a logical explanation is that the city might be better off by relaxing parking restrictions to help DVs finishing their routes faster, than by tightening regulations that increase DVs cruising time and cause more congestion. Since the benefits and responsibility for the implementation of more relaxed illegal parking measures lie entirely in the city's hands, is an additional incentive to consider it as a feasible traffic management policy.

Keywords: *Traffic simulation, city logistics, urban logistics, illegal parking*

Networks, synchronisation and fatigue: Modelling busy meeting schedules

Takuma Adams[a] **and Alexander Kalloniatis**[a]

[a] *Joint & Operations Analysis Division, Defence Science & Technology Group, Canberra 2600 Australia*
Email: Takuma.adams@dst.defence.gov.au

Abstract: Modern workplaces have long been dominated by meeting schedules as the basis for decision making. This has become accentuated in COVID-impacted times, where virtual technologies have removed the physical impediments to holding a meeting (find a physical room, enable people to physically separate from their current work to go to the room) so that workers in 2020-21 often face day after day of back-to-back meetings (DeFilippis et al 2020). Such crammed scheduling can be both cognitively draining and remove the space in the day for the actual conduct of work (Karl et al 2021), while nonetheless promoting the otherwise important factor of human-to-human interaction. What analytical framework can test how these elements can be balanced? In this paper we provide a mathematical model that addresses this question. The model is founded on a representation of synchronisation dynamics on networks, where agents are effectively phase oscillators interacting with each other through a graph topology and with some strength of coupling; this is the famous Kuramoto (1984) model. Typically, studies with this model have used static graphs. However, meeting schedules are very much examples of dynamical networks facilitating synchronization of multiple decisions, both within the conduct of any individual meeting and across the entire schedule (Sauer et al. 2015). A potential mathematical paradigm for this type of time-dependent interaction is the approach of `blinking networks' (Faggian et al. 2019), which has initially been applied to the meeting schedule problem in the Command and Control (C2) context by (Kalloniatis 2020). In this paper we further extend this model to incorporate time-dependent fatigue factors using such research as seen in (Hunter & Wu 2016), where continuous interaction in meetings, while generating a positive synchronising effect on decision cycles, also attenuates the coupling strength. We consider a fictitious set of meeting participants and key meetings they are required to attend. We conduct numerical experiments examining alternate scenarios for where to put breaks within the meeting schedule. By measuring the Kuramoto order parameter for synchronisation we are able to evaluate the success or otherwise of a schedule design that balances across the requirements of bringing coherence to distributed decision making and capacity for workers to take the time to develop quality in their inputs to those decisions.

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Keywords: *Meetings, networks, synchronisation, mathematical modelling*

Literature review on medical evacuation in military

S. Biswas[a], H. H. Turan[a], and S. Elsawah[a]

[a]*Capability Systems Centre, University of New South Wales, Canberra, Australia*
Email: sumana.biswas@adfa.edu.au

Abstract: Military Medical Evacuation (MEDEVAC) is the timely and efficient movement of the wounded, injured, or ill military personnel under medical supervision to medical treatment facilities (MTF), as an integral part of the treatment continuum. The MEDEVAC system needs to ensure that the right casualty is collected from the right pick-up point, transported to the right destination in the right platform, with the right medical escort, in the right time. The main goal of MEDEVAC is to reduce mortality among critically injured combat casualties. In order to achieve this goal, several decisions ranging from selecting the location of MTFs to routing and dispatching of evacuation assets have to be optimally executed. The MEDEVAC process directs casualties from point-of-injury (POI) to appropriate health facilities based on required treatment, evacuation platform availability and capacity of the destination medical facility. This MEDEVAC pathway can be divided into three phases; namely, forward, tactical, and strategic as depicted in Figure 1. These phases are based on the level of care provided in the MTFs. Military organize the MTFs into five levels or "roles" of care where each role corresponds to the level of care provided. This literature review paper focuses specifically on these three phases of MEDEVAC system and the decisions problems involved in these phases.

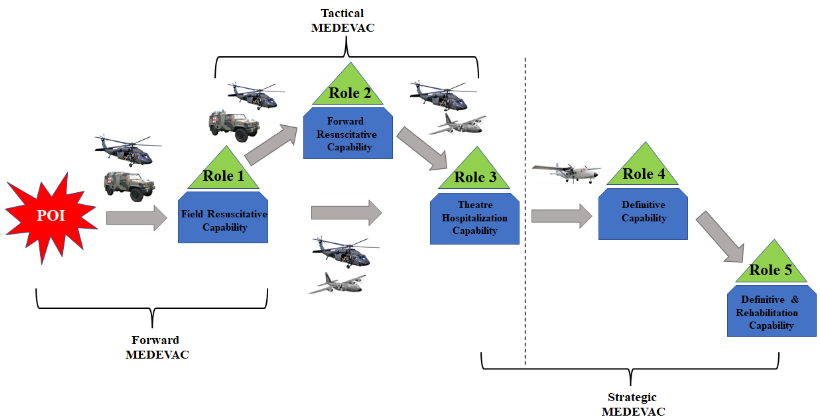

Figure 1. Medical evacuation pathway

Over the last years, a few review papers have discussed the evolution of military MEDEVAC systems. However, no literature review has been conducted on the total care pathway of MEDEVAC systems. The significant challenge of this review paper is to fill this gap. Materials and Methods: This review summarizes the publicly available literature and reports. The literature comprises of journal articles, conference proceedings, books, and thesis. The electronic search included PubMed, Scopus, Web of Science, and Google Scholar. Results: We reviewed 85 records from 1997 through August 2021. Most of the paper is based on the medical evacuation by US Army. It is identified that a good number of research work has been done on Forward MEDEVAC and most of them analyse the deployment of aeromedical evacuation. The number of papers on Strategic MEDEVAC are very low. It is also identified that the number of papers related to determining the optimal capability of Forward MEDEVAC and Tactical MEDEVAC system (by minimizing the travel time) are still limited. Conclusion: The management of the total pathway of MEDEVAC system has always remained a challenge. In casualty care systems or MEDEVAC systems, the incorporation of all the advanced knowledge and technology in an optimal way can reduce mortality and morbidity. It is identified that; the most significant reason of patient survivability is the rapid movement of casualties from the POI to higher role of medical care and proper treatment. Therefore, in the MEDEVAC process, leaders and planners should put emphasis on maximising the use of time and on (efficient) medical capacity.

Keywords: *Medical evacuation, military medical support system, medical treatment facilities, combat casualties, aeromedical evacuation*

EXTENDED ABSTRACT ONLY

A discrete-event simulation approach to improve the planning efficiency of the Australian Institute of Marine Science's Great Barrier Reef Long-Term Monitoring Program

Guvenc Dik[a] and Paul Corry[b]

[a,b] School of Science, Queensland University of Technology, Brisbane, 4000, Australia
Email: g.dik@qut.edu.au

Abstract: The Australian Institute of Marine Science (AIMS) have been monitoring the coral health and fish abundance of the Great Barrier Reef (GBR) for over 35 years within the scope of the Long-Term Monitoring Program. The GBR is threatened by the consequences of intertwined problems such as changing water quality, coral bleaching, crown-of-thorns starfish outbreaks, severe cyclones and intense heatwaves caused by climate change (AIMS, 2021). Currently only 0.03 percent of the GBR can be monitored every year due to its geographic vastness, logistics and funding limitations (AIMS, 2021).

The AIMS has been using diver-based techniques such as manta tow and transect surveys for monitoring the GBR. The manta tow technique involves two snorkel divers visually assessing the reef health as they are towed by small tenders travelling at a constant speed along the perimeter of the reef. Whereas the transect survey technique is performed with divers swimming across permanently marked sites undertaking image-based surveys. The evolution of autonomous systems has created an opportunity for AIMS to adopt more effective and efficient monitoring techniques. The traditional manta tow process is proposed to be supplanted with autonomous surface vehicles deployed from the research vessel and the transect process to be upgraded with autonomous underwater vehicles deployed at the permanent sites from tenders.

In this project, we developed a series of discrete-event simulation models to evaluate the efficiency of diver-based survey techniques and their autonomous counterparts. The models abstract the behavior of a single trip, single vessel, multi-tender, multi-device (autonomous), multi-observer, multi-reef, multi-process monitoring problem. Monitoring processes are subject to spatial, sequential, temporal constraints and regulations. We considered reef positions, reef monitoring sequences, feasible steaming and monitoring time windows, lunch and decompression breaks. Furthermore, we factored in the reliability rates of autonomous vehicles and weather conditions which may lead to extended operational delays.

The feasibility of simulation runs is maintained through a violation detection and avoidance model. This model makes use of duration approximation and scheduling equations in decision points, such as before steaming from a reef to another reef or before starting a low priority modelling resolution monitoring process. However, sub-simulations are invoked in rather complex situations where parallel and sequential processes must be performed under stochastic weather conditions and reliability factors. Running sub-simulations within a main simulation is a time-consuming yet robust approach to detect and avoid infeasibilities.

Several scenarios are investigated to validate the behavior of the developed models. Our analysis indicates that the efficiency and effectiveness of the monitoring operations depends on resource levels, reef visit sequences, weather conditions, and autonomous vehicle reliability factors. Among the simulated scenarios, low reliability autonomous vehicles coupled with unsuitable weather conditions and narrow monitoring time windows can lead to the most elongated and costly monitoring operations. The simulation models are adopted by AIMS as a decision support tool with the institute continually exploring time and cost-effective reef monitoring scenarios through recalibrating the built-in parameters.

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Keywords: *Ecology, discrete-event simulation, The Great Barrier Reef, The Australian Institute of Marine Science Long-term Monitoring Program, logistics*

MOOR: Model-based Offline Reinforcement Learning for Sustainable Fishery Management

Jun Ju [a], **Hanna Kurniawati** [b], **Dirk Kroese** [a] **and Nan Ye** [a]

[a]*School of Mathematics and Physics, The University of Queensland, St Lucia, QLD 4072, Australia*
[b]*Research School of Computer Science, Australian National University, Canberra ACT 0200, Australia*
Email: jun.ju@uq.net.au

Abstract: Fisheries play multi-faceted roles in our society, economy, and environment, and the management decisions often involve competing driving forces. The need to account for multiple and possibly objectives make sustainable fishery management a highly challenging task. This is further compounded by the large amount of uncertainties present in the problem: in particular, our knowledge of the fishery system is limited, and the state of the fishery system is not directly observable.

The Partially Observable Markov Decision Processes (POMDPs) — a general principled framework for sequential decision making for partially observable environments — is well-suited for sustainable fishery management: it is able to account for the long-term effect of actions, and it can conveniently take uncertainties into account. A few recent works have explored the potential of using POMDPs for sustainable fishery management. In this paper, we leverage recent advances in two sub-fields of machine learning, namely, deep learning and reinforcement learning, to develop a novel approach for sustainable fishery management using POMDPs.

We first propose an offline reinforcement learning approach for sustainable fishery management. While typical reinforcement learning approaches learn an optimal policy by directly interacting with the environment, offline reinforcement learning approaches learn an optimal policy using a dataset of past interactions with the environment. The use of past data instead of direct interventions is a highly desirable feature for fishery management — this has been exploited in the literature of management strategy evaluation too. We believe this perspective will allow us to tap into recent advances in offline reinforcement learning.

Our second contribution is a new algorithm, MOOR, which stands for MOdel-based Offline Reinforcement learning algorithm for sustainable fishery management. MOOR first learns a POMDP fishery dynamics model using catch and effort data, and then solves the POMDP using a state-of-the-art solver. In the model learning step, we view the POMDP fishery dynamics model as a recurrent neural net (RNN), and leverage RNN learning techniques to learn the model. This presents some new challenges, but we show that these can be overcome with a few tricks to yield a very effective learning algorithm.

Finally, MOOR demonstrates strong performance in preliminary simulation studies. The learned models are generally very similar to the true models. In addition, the management policies obtained using the learned models perform similarly as the optimal management policies for the true models. While previous POMDP studies for fishery management evaluate policy performance in the learned model, we evaluate the policy in the true model, thus our results suggest that it is possible to develop a POMDP approach that can be robust against mild model learning error. Moreover, although this paper focuses on fisheries applications, the approach is general enough for other problems where the dynamics are nonlinear, though further research are needed to understand the extent and efficiency of the method on other domains. Our source code will be made available after the publication of the work.

Keywords: *Offline reinforcement learning, fishery management, POMDPs*

A novel graph-theoretical approach to find a reduced set of Pareto optimal solutions for multi-objective optimisation problems: with a case study in defence capability management

S. Kahagalage[a, b], H. H. Turan[a], F. Jalalvand[a], and S. El Sawah[a]

[a]*Capability Systems Centre, University of New South Wales, Canberra, Australia*
[b]*School of Mathematics & Statistics, The University of Melbourne, Melbourne, Australia*
Email: kahagalages@unimelb.edu.au

Abstract: Many real-world problems have multiple objectives, and most often, they are conflicting. Therefore, multi-objective optimisation problems and their solution algorithms are of great importance. However, unlike single-objective optimisation problems, which result in a single solution, multi-objective optimisation problems most often lead to a large set of trade-off solutions called Pareto optimal solutions (Pareto set). As all the solutions in this set are considered equally good with some trade-offs, on the one hand, it is sometimes difficult for the decision-makers to make their decisions, especially in the absence of subjective or judgmental information (e.g., the priority or preference of the objective functions over the others). On the other hand, analysing all solutions is time-consuming and hence not practical.

There are three primary methods to obtain a reduced set in the existing literature: namely, priori, interactive, and posterior approaches. In the priori and interactive methods, the decision-maker puts his/her preferences of objective functions before or during the optimisation process, respectively. As opposed to these two methods, in this research, we focus on posterior methods because they provide an overall picture to the decision-maker. Several posterior methods have been proposed in the past, such as clustering (e.g., *K*-means) and ranking (e.g., Analytical Hierarchy Process). In clustering methods, first, clusters are obtained for the Pareto set. Then, a representative solution is extracted from each cluster to form the reduced set (e.g., the solution at the cluster centre or one closest to the ideal solution of the cluster). However, the reduced set may not contain extreme solutions and, hence, does not capture the diversity of the entire Pareto set. To alleviate the shortcomings of the existing approaches, we propose a novel graph-theoretical approach to obtain the representative solutions from each cluster and other extreme solutions. The proposed approach is based on the connectivity (e.g., degree) in the feature space (Pareto state-space). The representative solutions and extreme solutions then constitute a reduced set.

We test the applicability of the proposed method on a multi-objective optimisation problem that is motivated by the recent modernisation investments of the Royal Australian Navy. In particular, we consider three submarine fleet transition options. We solve the optimisation problem by using a simulation-based optimisation technique. Then, we employ the proposed method on the obtained Pareto set for each fleet transition option to extract a reduced set. We compare the reduced set obtained from the proposed method with two traditional posterior methods: the reduced set obtained from the solution at the cluster centre and the solution closest to the ideal solution of the cluster. The Hypervolume indicator (HI) and the maximum spread (MS) are used for the comparison. The HI measures the volume of the trade-off space while the MS compares the Pareto optimal solutions with the ideal and the worst solution. We observed at least 10% and 3% increase in the HI compared to reduced sets which are obtained from the solution closest to the ideal solution and solution at the cluster centre, respectively. The results from the MS also revealed at least 1% increase compared to the two traditional methods tested. Thus, the proposed method which finds the reduced set is also better at capturing the diversity of the entire Pareto set. Hence, the proposed method gives the decision-maker a small set that almost covers the characteristics of the entire Pareto set. Even though the proposed method can be applied to any multi-objective optimisation problem, we are yet to test its efficacy in other applications.

Keywords: *Multi-objective problems, simulation-based optimisation, defence capability management, clustering, graph theory*

Real-time ensemble assimilation of image-based canopy data into a process-based model for improved vineyard forecasting, situational awareness and decision-making

Matthew J. Knowling [a], Jeremy T. White [b], Cassandra Collins [c], Dylan Grigg [c], Seth Westra [a], Bertram Ostendorf [d], Bree Bennett [a], Ayman H. Alzraiee [e], Wayne Kiely [c] and Vinay Pagay [c]

[a] *School of Civil, Environmental and Mining Engineering, Faculty of Engineering, Computer and Mathematical Sciences, The University of Adelaide, Australia*
[b] *Intera Inc., Fort Collins, Colorado, USA*
[c] *School of Agriculture, Food and Wine, Faculty of Sciences, The University of Adelaide, Australia*
[d] *School of Biological Sciences, Faculty of Sciences, The University of Adelaide, Australia*
[e] *United States Geological Survey, Sacramento, California, USA*
Email: matthew.knowling@adelaide.edu.au

Abstract: Process-based crop models are used increasingly for agricultural decision support due to their ability to predict farm outcomes under different operational decisions and with respect to exogenous factors. The assimilation of observed data into crop models can enhance predictive reliability by reducing the uncertainty surrounding key farm outcomes such as yield, and mitigate issues arising from model inadequacy. Despite the ability of several crop models to simulate grapevine growth and development (Knowling et al., 2021), together with the unprecedented volume of data available due to 'digital agriculture' revolution, the capability of formal model-data assimilation techniques to improve vineyard forecasts and situational awareness has not been realized.

Here we apply a recently developed implementation of the iterative ensemble Kalman filter (EnKF) (Alzraiee et al., in prep) to update dynamically both input parameters and states associated with a crop model that is specifically designed to simulate grapevine growth and development (Walker et al., 2020). Model parameters and states are updated on the basis of daily climate/weather data, and weekly/fortnightly leaf area index (LAI) data. Using this approach, we evaluate the "worth" of data in terms of their ability to enhance yield forecast reliability on a daily basis throughout the growing season (e.g., during different canopy development and phenological stages). The benefit of improved forecast reliability in terms of vineyard situational awareness and operational water management decision-making is explored by considering the outcomes of a range of irrigation scenarios for the remainder of the growing season.

A South Australian vineyard case study is considered, where vision-based LAI data (De Bei et al., 2016) have been collected. The entire data assimilation workflow is currently being incorporated into an online platform that is designed for grower decision support.

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Keywords: *Crop model, data assimilation, uncertainty, decision support, leaf area index*

Evaluating instruction quality across narrative modality using measures of real-time cognitive load

S. P. Smith[a], K. Blackmore[a], S. Wark[b] and M. Nowina-Krowicki[b]

[a]*School of Information and Physical Sciences, University of Newcastle, Callaghan, NSW 2308, Australia*
[b]*AI for Decision Analytics, Joint Warfare & Operations, Joint & Operations Analysis Division, Defence Science & Technology Group, South Australia*
Email: shamus.smith@newcastle.edu.au

Abstract: Planning and operations tasks in complex environments place high information processing demands on decision makers. Within these environments, decision makers must simultaneously execute an operational plan, developed and enacted under pre-existing contextual information, whilst directing tasks and responding to real-time events. Receiving tasking and updated scenario information, in situ, can place significant cognitive load on decision makers.

In the research presented here, we consider the intersection between information delivery modalities and real-time cognitive load. Three information delivery conditions, namely a control condition containing only text and image-based media (see Figure 1:Right), a virtual human condition, using the Defence Science & Technology Group Virtual Human Storytelling system, combining multiple forms of visual prompts (virtual human avatar, as well as images) as well as audio cues (see Figure 1:Left), and an audio condition combining both image and audio cues only were considered.

Figure 1. Example information delivery modalities. Left: Virtual Human condition. Right: Text condition.

The results are promising for use of the Virtual Human Storytelling system. Across navigation, map annotation and resource allocation tasks, participants with instruction via the virtual human avatar tended to have higher performance scores. These participants also demonstrated better cognitive load profiles when compared to participants who had text or audio-based instruction. The research provides novel and interesting insights into the potential benefits of task instruction delivery for enhanced human performance in complex operating environments.

Keywords: *Decision support, virtual humans, simulation, cognitive load, information delivery*

The closed loop military maintenance workforce: A simulation-based optimisation approach

Kurt R. Withers [a], Hasan Hüseyin Turan [b], Sanath Kahagalage [b], and Sondoss El Sawah [b]

[a]*The University of New South Wales at the Australian Defence Force Academy*
[b]*Capability Systems Centre, University of New South Wales, Canberra, Australia*
Email: k.withers@student.unsw.edu.au

Abstract: Workforce simulation modelling allows organisations to predict workforce skill requirements and implement strategies to meet foreseeable industry demands. The maintenance workforce increases the simulation model's complexity due to the co-dependencies associated with variables such as asset reliability, workforce composition, and maintenance policies. The military maintenance workforce differs from the usual maintenance workforce model due to its unique closed loop environment, which adds further complexities to the simulation model.

This paper uses a typical Australian Defence Force (ADF) technical workshop to explore the effect that workforce composition and posting policies have on a workshop's ability to maintain critical asset in a ready for issue (RFI) state. As the solution approach, a state-of-art Discrete Event Simulation (DES) model is coupled with a genetic algorithm (GA), which is known as simulation-based optimisation, to find best strategical decisions regarding posting and workforce composition in the technical workshop within the defence environment.

The objective of the DES is to explore the effects of utilising different posting policies and workforce compositions in a ADF technical workshop. We first assume that the asset transfer and time between asset transfer are not optimised for the associated workshop workforce. This simulates a situation in which an ADF workforce has been stood up and asset transfer is set on mission requirements rather than maintenance considerations. This phase contains posting policies of a purely military workshop for a 2, 3, and 4 year period. Next, the workforce used for a 2 year posting policy is altered and members are replaced with Australian Public Service (APS) staff. The primary focus of this work is the use of simulation-based optimisation to optimise the asset transfer amount and rate in order to improve workshop mean and range for assets in RFI state.

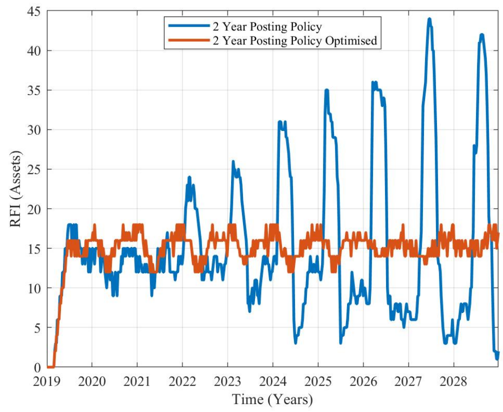

Figure 1. Effect of simulation-optimisation on the number of RFI assets.

The findings reveal that a mixed workforce composition provides greater workshop flexibility. There is up to a 10% increase in the mean RFI asset availability and a 55% decrease in the RFI variance when a mixed workforce composition is utilized. Further, simulation-based optimization leads to 9% mean increase and 80% variance reduction in the number of RFI assets compared to unoptimised results. The purely military workshop 2 year posting policy results are shown in Figure 1.

Keywords: *Defence, maintenance, workforce composition, posting cycle, simulation-based optimisation, genetic algorithm*

Using machine learning models to predict the solutions for optimization problems

Mahdi Abolghasemia [a], Babak Abbasi [b], Toktam Babaei [c] and Zahra HosseiniFard [d]

[a] *Department of Econometrics and Business Statistics, Monash University, Caulfield, VIC 3162, Australia*
[b] *Department of Information Systems and Business Analytics, RMIT University, Melbourne, VIC 3000, Australia*
[c] *School of Mathematical Sciences, Queensland University of Technology, Brisbane, QLD 4000, Australia*
[d] *Faculty of Business and Economics, The University of Melbourne, Parkville, VIC 3010, Australia*
Email: babak.abbasi@rmit.edu.au

Abstract: Using machine learning in solving constraint optimisation and combinatorial problems is an active research area in both computer science and operations research communities. This research aims to predict a good solution for constraint optimisation problems using advanced machine learning techniques. It extends the work of Abbasi et al. (2020) to use machine learning models for predicting the solution of large-scaled stochastic optimisation models by examining more advanced algorithms and various costs associated with the predicted values of decision variables. It also investigates the importance of loss function and error criterion in machine learning models where they are used for predicting solutions of optimisation problems.

The results indicate that we can use ML models to forecast the optimal values of the parameters with up to 98% similarity to the optimal solution while committing to the constraints over 99% of the times. We investigated the role of loss function in predicting the solutions for optimization problems. To do so, we trained LightGBM models with MAE, MSE and Huber loss functions and showed that using MAE loss function often leads to a better performance than using MSE loss function, while Huber loss averages the MAE and MSE results. Therefore, we suggest using ML models with appropriate loss functions to predict the solutions of optimizations models. While well-tuned ML models can generate competitive results, they perform significantly faster than the commercial solvers and they are cheaper in terms of costs.

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Keywords: *Optimisation, forecasting, machine learning, loss function, blood supply chain*

Applying Neural Networks to conflate vector road datasets

Artiom Bondarenco [a], **Andrew Higgins** [a], **Stephen McFallan** [a], **Adam McKeown** [a] **and Caroline Bruce** [a]

[a] *CSIRO Land & Water, Australia*
Email: Artiom.Bondarenco@csiro.au

Abstract: An accurate conflation of geospatial datasets is a classic GIS problem. Several approaches exist to perform vector to vector conflation, however they either do not work well with big data or require hard-coding of rules to determine the best fit between conflated features. This quickly can become extremely complex and time consuming with big and diverse geospatial datasets.

The Transport Network Strategic Investment Tool (TraNSIT) uses geospatial datasets from dozens of sources, often involving millions of data points. An accurate conflation of these datasets is critical for providing the range of variables required for the tool's road and rail transport analysis.

We developed a Deep Feed Forward Neural Network (DFFNN) using Keras package in Python to assign a B-double road train access rating to each segment of the commercial HERE road network based on the National Heavy Vehicle Regulator (NHVR) classification. Eight features were used as an input into the neural network model to evaluate spatial relationship between HERE and NHVR network segments. These features were either extracted from the HERE network (ramp, roundabout) or manually created using Python's GeoPandas package (near distance, Haversine distance, Manhattan distance, latitude and longitude difference, and bearing difference). The DFFNN was trained on ~2 million manually conflated network segments and then classification was carried out on a network dataset of ~23 million segments. The resulting road network dataset represented a B-double road train access rating with ~98% accuracy.

With further training and modifications, our model could serve as a powerful tool for a quick and accurate conflation of other similar vector datasets, such as other types of road train access, bridge limits, road safety, etc.

Keywords: *Deep learning, conflation, vector datasets, TraNSIT*

Robustness of ML models in the classification of operational context simulated in network constrained environments

Robert Davidson [a]

[a] *Defence Science and Technology Group, Edinburgh, Adelaide, 5011, Australia*
Email: robert.davidson@dst.defence.gov.au

Abstract: The ability to optimally allocate resources within our computing systems relies on understanding the dynamic nature of priorities for tasks and resources. Context has been used to understand what prioritisation should be given to tasks enabling changes in resourcing to occur as needed. What is context? Dey et al. (2001) define context as "any information that can be used to characterise the situation of an entity". Operational context is used to describe the current set of tasks undertaken by the operator and associated asset and is applied in this instance to a search and rescue scenario conducted by Surf Life Saving South Australia. Identifying context requires information from different sources that will vary depending upon the domain of interest. This study identifies the impact of network degradation on the accuracy of classification of operational context. The machine learning (ML) algorithms' robustness was quantified with simulation using a real-time network emulator.

Three Surf Life Saving SA search and rescue (SAR) operations were broken down into the following stages: patrol, search, approach, rescue and unknown. A Random Forest supervised ML algorithm was trained on two of the three SAR scenarios with the third used for testing. A simulation environment was constructed to replay the SAR operation with modification of the network connectivity (0%, 50%, 80%, 95%,97%, 99%, and 100% packet loss) between the watercraft using the Extendable Mobile Ad-hoc Network Emulator (EMANE). The link quality of the Time Division Multiple Access (TDMA) network and the performance of the ML model were recorded in real-time as the replay of the scenarios unfolded. In addition, the interaction of the relationship between network degradation, SAR scenario and ML model performance was quantified.

The features identified as most important to the classification of operational context included speed, the direction of travel, the distances between assets and distance to home base. The relative importance of those features varied between operational stages, which was reflected in the interaction of performance of the ML model in classifying operational context between scenarios. The network state also impacted on how the ML models performed. The models did maintain classification accuracy as packet loss increased to 80% but steadily declined as packet loss increased to 95% and beyond.

ML models can be used to identify operational context using features calculated from GPS data. However, the reduced availability of that data required from assets within the region of interests when networks degrade will impact classification accuracy. Therefore, future work will investigate the feasibility of adding additional sources of contextually relevant data to identify operational context dynamically, evaluating if it is possible to offset the loss of information from a single source.

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Keywords: *Operational context, Random Forest Machine Learning, EMANE*

A large-scale multi-rider matching problem with reneging passengers: single source case

Jing Fu [a] **Lele Zhang** [b] **Kai Huang** [c] **and Zhiyuan Liu** [d]

[a]*School of Engineering, RMIT University, VIC 3000, Australia,*
[b]*School of Mathematics and Statistics, The University of Melbourne, VIC 3010, Australia,*
[c]*Department of Civil Engineering, Monash University, VIC 3800, Australia,*
[d]*School of Transportation, Southeast University, Nanjing, China*
Email: jing.fu@rmit.edu.au

Abstract: This paper studies a large-scale ride-matching problem with a single transport hub with a large number of passengers who are different in terms of destinations and travel preferences. Passengers with similar itineraries can match each other and share the same vehicle for their potentially different destinations; and reneging passengers, who become impatient and leave the service system after waiting long time for shared rides, are considered in our model. We aim to maximize the long-run average revenue of the ride service vendor, which is defined as the difference between the long-run average reward earned by providing ride services and the long-run average penalty incurred by reneging passengers. The problem is complicated by its scale, the heterogeneity of passengers, and the reneging behaviors. To this end, we formate the ride-matching problem as a specific Markov decision process and propose a scalable ride-matching policy, referred to as Bivariate Index (BI) policy. Through extensive numerical simulations for systems with real-world travel demands, it is demonstrated that BI significantly outperforms baseline policies.

Keywords: *Restless bandits, ride-matching, reneging passengers*

Data preprocessing for non-image data: using convolution neural networks for network intrusion detection systems

G. Glukhov [a] **and T. Lynar** [b]

[a] *School of Engineering and Information Technology, University of New South Wales, Canberra, ACT 2600, Australia*

[b] *School of Engineering and Information Technology, University of New South Wales, Canberra, ACT 2600, Australia*

Email: g.glukhov@unsw.edu.au

Abstract: Application of machine learning models in network intrusion detection systems has been the subject of extensive investigation and testing. Modern day networks produce data in quantities that put more emphasis on the accuracy and precision of the intrusion detection systems. This produces the drive for more accurate and time-efficient intrusion detection systems, and machine learning was investigated as a viable solution. Research into machine learning models in other fields has yielded several different algorithms and approaches, highly specialised to those particular data types. Testing for intrusion detection has found that the models that process the network data best tend to yield higher accuracy and lower false-positive rates, whereas those models that perform best on their original data have struggled. One such model that under performed in intrusion detection when compared to the original field is convolution neural network. This paper aims to investigate preprocessing methods for network data to increase the effectiveness of using a convolution neural network model as part of a network intrusion detection system. Specifically, the paper will analyse the use of the DeepInsight architecture,using a modified t-distributed stochastic neighbour embedding technique, the positioning of features in isolation and a control class of simple reshaping data from vector to matrix form.

Keywords: *Artificial intelligence, neural network, data preprocessing, feature mapping, network intrusion detection*

Blood units substitution decisions: a stochastic optimisation approach

Zahra HosseiniFard [a], **Mostafa Khatami** [b] **and Babak Abbasi** [c]

[a] *Faculty of Business and Economics, University of Melbourne, Melbourne, VIC 3010, Australia*
[b] *School of Mathematical and Physical Sciences, University of Technology Sydney, Sydney, Australia*
[c] *Department of Information Systems and Business Analytics, RMIT University, Melbourne, VIC 3000, Australia*
Email: zahra.h@unimelb.edu.au

Abstract: Substitution is known as an efficient strategy to mitigate supply chain risk in dealing with demand uncertainty. Substitution is generally considered in designing effective inventory replenishment policies, as it can reduce the constraints imposed by limited storage capacity and alleviate the negative impact of demand uncertainty. If efficiently designed, it can reduce shortage and holding costs. A well-known example of substitution practice is in blood transfusion of different compatible blood types at hospitals or emergency departments. Among different blood types, O-negative is most commonly used for substitution, due to its compatibility property, which means it can be given to any patient without knowing their blood type. A recent study by Australian Red Cross Lifeblood (Hirani et al. 2017) revealed the issue of O-negative over-ordering at hospitals. They found that O-negative red cells units were mainly transfused to prevent wastage and in-close-to-expiry situations whereas identical ABO groups may have been more suitable. This reveals the issue of O-negative over-ordering at hospitals.

Substitution decision in hospitals is complex, in addition, blood supply chain has several properties that differentiates it from well-studied supply chains. It can be considered as a two-echelon inventory system where blood banks receive blood donations at the first echelon while demand is realised at the second echelon e.g., at hospitals or emergency departments. Replenishment in the blood bank occurs by blood donors, therefore, it is stochastic and scarce. Moreover, the collected blood is perishable. This research focuses on ordering policy with consideration of effective substitution decisions for red blood cells at hospitals and emergency requisition from the blood service with consideration of the optimal substitution policy that has not been explored in the blood supply chain literature. We consider demand and supply stochastic. The mathematical modelling approach to the problem is by considering a stochastic optimisation model under substitutions, uncertain demand, stochastic supply, perishable items with fixed shelf life and the age of items in inventory. To improve the performance of blood supply chain, the outdates and shortages and the age of transfused items should be minimised. To have more realistic assessment of the costs of a replenishment policy of the resulting optimal policies, this research develops a combination of price-based and inventory-based substitution where preferences on product substitution are driven by product price and attributes.

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Keywords: *Blood supply chain, perishable inventory, two-stage stochastic optimisation*

Joint optimization of privacy and communication cost for federated learning in IoT

Yingxin Liu and Jingjin Wu

Department of Statistics, Division of Science and Technology, Beijing Normal University-Hong Kong Baptist University United International College, Guangdong, China
Email: yingxinanna@163.com, jj.wu@ieee.org

Abstract: Emerging technologies, such as edge computing and artificial intelligence, generate amounts of new possibilities for the development of the Internet of Things (IoT). However, the end users of IoT applications are more and more concerned about their data privacy, as conventional AI algorithms for common purposes in IoT applications (e.g., task scheduling and computational offloading) all require private and sensitive data to be transmitted to the server and thus may incur significant data leakage risks.

Federated learning (FL) has been recently proposed to address the privacy issue. FL is a distributed machine learning framework that trains a shared model collaboratively while keeping clients' sensitive data on their own devices. Without exchanging raw user data between the federated server and clients, private data generated by IoT devices are avoided from being exposed to untrustworthy servers. However, recent studies show that even only sharing local parameter updates from users to the federated server is still susceptible to attacks such as the gradient-based reconstruction, which may obtain the weights trained in neural networks and then divulge certain private information.

On the other hand, if the federated server collects too little and/or inaccurate information from the clients, the training quality may not be acceptable. It will in turns lead to higher communication costs due to possibly necessary re-transmissions. In this study, we consider a differential privacy based approach, where artificial noises are added to sensitive parameters before model aggregation to preserve original information from possible leakage, in order to jointly optimize client privacy level and communication cost.

Specifically, the communication cost is the sum of total communication time and total computation time to complete a training with satisfactory quality, while the privacy level of each aggregation is quantified based on the inequality for the trade-off between privacy and convergence performance in federated learning obtained in (Wei *et al.* 2020). We let the convergence performance in each iteration be a constant number and obtain equality for the privacy level in each iteration round. It shows that the privacy level is related to the number of selected clients and the number of aggregation times.

We also consider subchannel selection and subcarrier allocation, which may affect the communication time, in our joint optimization problem. We exploit a deep deterministic policy gradient (DDPG) algorithm to find the optimal solution which consists of clients selection, subchannel selection, and subcarrier allocation. The DDPG determines the solution using a value function that includes an actor deep neural network (DNN) and a critic DNN. The value functions are approximated by using the deep Q network (DQN). Particularly, we consider the federated server (the aggregator) as an agent that learns the resource allocation policies and client selection strategy.

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Keywords: *Deep deterministic policy gradient (DDPG), federated learning, differential privacy, internet of things (IoT), resource allocation*

System dynamics applications for defence combat modelling: preliminary insights from a literature exploration

G. Cunico [a], **S. Elsawah** [b], **M.S. Gary** [a], **T. Cao** [c], **L. Kosowski** [c], **M.K. Richmond** [c]

[a] *Business School, University of New South Wales (UNSW), Sydney, New South Wales, Australia*, [b] *Capability Systems Centre, UNSW Canberra*, [c] *Defence Science & Technology Group, Edinburgh South Australia*
Email: g.cunico@unsw.edu.au

Abstract: System dynamics (SD) encompasses a suite of conceptual and simulation methods used to study complex system behaviour over time. The structure of an SD model represents the cause-effect relationships and feedback loops in the system. SD models include stocks and flows to map system structure. Stocks, also known as accumulations, characterise the system state and change in response to flows (also known as rates). For example, the number of armoured vehicles involved in a conflict could be represented as a stock that changes in response to the attrition rate. SD causal mapping and conceptual models help teams generate ideas and facilitate shared understanding by developing a coherent representation of the problem. The causal representation of SD models provides a useful means for stakeholders to understand dynamic problems, reason about the effect of changes, and identify potential leverage points. The use of simulation methods to examine dynamic behaviour over time enables assessing alternative decisions under a range of scenarios, evaluating the veracity of different views and providing evidence linking assumptions and outcomes.

SD has been used to analyse a range of different defence decisions and topics. In this paper, we focus on combat modelling as an important research and application area in defence modelling. Given the lack of synthesis on the use of SD in combat modelling, this paper provides a preliminary exploration of the topic to identify the most salient points and set the groundwork for future research. We review and synthesise published SD applications in combat modelling to understand how SD models have been used to analyse alternative combat force designs and strategies. The review provides a starting point for researchers who want to understand the SD combat modelling literature and those who want to build SD models to examine combat dynamics.

The paper is organised around addressing four research questions: (i) why use SD for combat modelling, (ii) where does SD combat modelling fit within the broad SD defence modelling domain, (iii) what recurrent themes and operationalisation can be found in SD combat models, and (iv) what is the SD combat modelling state of the art? We conclude by identifying promising future research directions, such as: applying SD to explain the impact of new technologies involving the integration of autonomous systems to combat.

Keywords: *System dynamics, defence modelling, combat modelling*

Model-supported case study of 1999 East Timor Crisis

M.S. Gary [a], A. Stephens [b], A. Coutts [b] and M.K. Richmond [b]

[a] *School of Management & Governance, UNSW Sydney, New South Wales;* [b] *Defense Science & Technology Group, Edinburgh South Australia*
Email: sgary@unsw.edu.au

Abstract: Design of the future Land Force requires decision making on force structures and capabilities under uncertainty in a complex, dynamic environment. System dynamics models built from the mental models of force design decision makers can surface their biases and assumptions, and potentially drive improvements in the force design process. This study explores the use of a system dynamics (SD) model-supported case study to analyse potential future Land Force designs for an Australian led generic stability operation within the Asia-Pacific region. The 1999 crisis in East Timor serves as the historical case study for the model because it closely matches the force design problem of interest.

The team developed a proof of concept SD model representing, at a high level, the violent militia attacks that erupted in East Timor just after the 1999 vote for independence. The model assumptions were based on data collected from: (1) interviews of subject matter experts (SMEs), (2) written publications about the 1999 East Timor crisis, and (3) expertise of core project team members. All SMEs had knowledge in key scenario dimensions, force design, and/or land force operations and effects. The interviews were semi-structured and ranged from 45–90 minutes in duration. The interviewees included 5 DST Staff with experience in Land Force design and 10 Military staff in Army HQ with roles in strategy and/or future Land Force design holding rank from Major to Major General.

The number of Active Militia Members in East Timor after the pro-independence vote by the general population is a key stock, or state variable, in the model. The militia members did not support independence and in retaliation committed violent attacks against the local population. In response, the Australian Defence Force (ADF) led a United Nations Coalition force to the island to restore security. Militia members remain active until they either: (1) become detained or eliminated by Coalition forces or (2) retreat across the border into West Timor. Other stocks represented in the model include: the number of Coalition Troops in East Timor (driven by test inputs for the change in troops), the Fraction of Coalition Operations that are Kinetic (versus fraction of Indigenous Capacity Building & Population Support Operations), Quality of Essential Infrastructure on the island, and Population Support for Host Nation Government. The model also includes the potential effects of Information Operations (IO) in multiple places, enabling exploration of future IO capabilities. Figure 1 shows a simplified stock and flow diagram of the model. Simulation runs demonstrate the model can qualitatively match the dynamics of the historical case. As a next step, the team will collect quantitative case data to test and build more confidence in the model. Subsequently, the model can be calibrated to represent a future stability operation to evaluate the effectiveness of alternative Force designs.

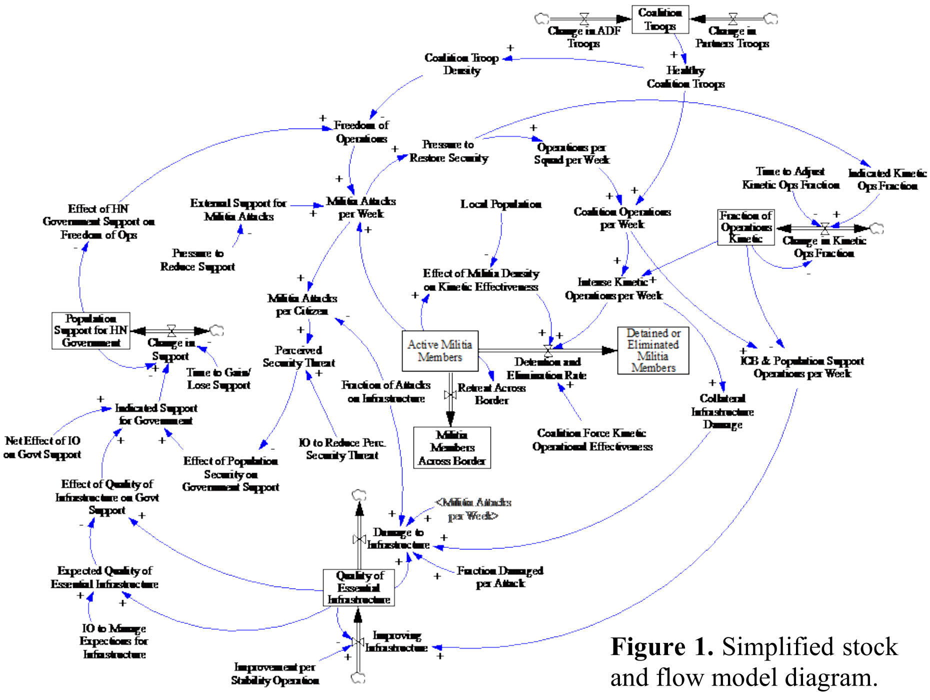

Figure 1. Simplified stock and flow model diagram.

Keywords: *System dynamics, stability operation, force design, information operations*

Critical minerals and the Clean Energy Transition

William Grace [a]

[a] *Australian Urban Design Research Centre, University of Western Australia, Perth, 6000, Australia*
Email: bill.grace@uwa.edu.au

Abstract: Over recent decades many authors have pondered the potential for 'peak minerals', i.e. the possibility that the supply of economically critical minerals could be constrained, either through scarcity or the economic and / or environmental cost of extraction and production. In this article I consider four metals that are key to the transition from fossil fuels to a clean energy future: copper, cobalt, zinc and molybdenum.

The recent International Energy Agency report 'The Role of Critical Minerals in Clean Energy Transitions' (International energy Agency, 2021) contains projections for demand of these minerals to 2040 under (inter alia) the Sustainable Development Scenario (SDS). The SDS assumes a trajectory under which climate change is managed in line with the Paris Agreement, meaning net global greenhouse gas emissions would be at or near zero by 2050. Under this scenario the demand for total minerals is projected to quadruple by 2040 from existing levels. The selected minerals are required to some extent for all elements of the clean energy transition, including generation, battery storage and distribution.

In this study I use a systems dynamics model to explore the various possible supply-demand trajectories for the selected minerals. Historical data for production, reserves and resources are drawn from Sverdrup et al (2017), Jowitt et al (2020) and the U.S. Geological Survey (USGS) annual Mineral Commodity Studies report.

Jowitt et al conclude that the Reserves of most metals have kept pace with production and "will not run out" in the next 50 years. Other authors (Harald Ulrik, Anna Hulda, & Kristin Vala, 2019; Harald Ulrik Sverdrup, Kristin Vala Ragnarsdottir, & Deniz Koca, 2017) have developed a sophisticated system dynamics model to explore potential resource scarcity over longer time periods for a number of minerals and conclude that peak production of copper will occur by 2045 and decline thereafter, and zinc will peak around 2100. Henckens et al (2018) conclude that virgin supplies of molybdenum will be exhausted "within fifty to hundred years".

The modelling study reported in this article uses plausible trajectories for global gross domestic product (GGDP) and existing and projected material intensity to explore supply-demand scenarios for the selected minerals to 2100, based on the increased demand associated with the clean energy transition. The results suggest that remaining stocks of these resources are likely to decline substantially by the end of the century and supply constrained for Cobalt by 2040-50s, Molybdenum by 2050-60s, and for Copper and Zinc in the 2060-70s, and this is delayed by only 20 years even if ultimate resource estimates are doubled from present projections. Increasing recycling rates for all materials will be important to avoid shortages as the world transitions from fossil fuel dependence to even greater minerals dependence.

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Keywords: *Minerals, metals, resources, clean energy, climate*

Operational effectiveness of future land combat teams: model conceptualisation

M.K. Richmond [a], **M.S. Gary** [b], **T. Cao** [a], **D. Blumson** [a], **L. Kosowski** [a], **K. Hock** [a], **S. Elsawah** [c] **and N. Kempt** [a]

[a] *Defense Science & Technology Group, Edinburgh South Australia,* [b] *School of Management & Governance, UNSW Sydney, New South Wales,* [c] *School of Engineering, UNSW Canberra, Australian Capital Territory*

Email: matthew.richmond@dst.defence.gov.au

Abstract: Modern land combat teams conduct a wide range of operations, including high intensity conflict, counter insurgency, humanitarian assistance, plus many more. Operating environments also span a diverse range, including (for example) urban, jungle and littoral, against a variety of different adversaries and threat levels. In the future operating environment, the complexity of operations will only increase. Consequently, future combat teams must be designed for a broad scenario space. Although there has been extensive operations research modelling of land combat operations, in general it focuses on high-fidelity detailed modelling or highly aggregated models. Neither of these two classes of land combat models enable rapid analysis of the operational effectiveness of future combat team performance. Further, most land combat models have tended to focus on representing kinetic factors and neglected non-kinetic and cognitive/social factors which have become critical to land warfare outcomes. We are interested in the ability to conduct medium-fidelity analysis of different proposed combat team designs[1] and particularly to evaluate the potential impacts of new and emerging technologies, in order to inform: (i) technology research & development priorities, (ii) insights for Land programs on potential technological impacts, (iii) explore the interplay between kinetic and non-kinetic effects, soft and hard factors, on combat effectiveness and (iv) to identify promising force designs to examine further using more detailed close loop simulation. We suggest that to achieve rigorous and responsive assessment of operational effectiveness (i.e., military utility) of incorporating new technologies into future combat teams across a range of (future) operational environments, including both hard and soft factors, requires a new class of model(s) conceptualised at a level of aggregation somewhere between the high-fidelity and highly aggregated models cited above.

This paper reports on the initial conceptualisation of a model to address this gap. The model focuses on representing the generic tactical level effects that a combat team must achieve to prosecute its required activities (e.g., assault, ambush, defend, etc.). By taking a generic approach to representing tactical level effects in the baseline model reported here, it is designed to be readily improved to consider a broad scenario space (as part of future work). We assume the generic effects and tasks required in future tactical land combat will persist, but the performance requirements will be influenced by the future operational environment and threat levels. Future combat team designs will be critical to how well the effects and activities can be performed.

We have focussed initially on a system dynamics (SD) modelling approach as it lends itself to the representation of a combat team at different levels of fidelity, ranging from highly abstract to very detailed. SD modelling also supports the representation of both quantitative and qualitative effects. We start by building a Baseline SD model representing a tactical land warfare combat team employing conventional (i.e., existing) technologies. A combat team force element is small enough to model quickly and to discriminate the impacts of specific technologies on operational effectiveness, but large enough to include combined arms capabilities and so key interdependencies between capabilities can be investigated. The Baseline model will provide the foundation for subsequent efforts to evaluate the impacts of future technologies compared with a combat team enabled with current technology, as well as "what-if" sensitivity analysis of more qualitative inputs such as morale and exploration of the scenario space. We discuss the next steps for further development of the baseline model and acknowledge the utility of incorporating other modelling techniques into a multi-method approach.

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[1] By combat team design we mean an organisational structure, key personnel and equipment, and concepts describing how the force will operate focusing on the differences from current doctrine.

Keywords: *Land combat, combined arms conceptual model, operational effectiveness evaluation, military utility assessment of emerging technology*

A system dynamics based serious game for solar panel waste management

Hengky K. Salim [a], **Rodney A. Stewart** [a] **and Oz Sahin** [a]

[a] *School of Engineering and Built Environment, Griffith University, Southport, Australia*
Email: o.sahin@griffith.edu.au

Abstract: Enabling a product stewardship scheme to manage end-of-life (EoL) solar photovoltaic (PV) panel waste is critical to prevent negative impacts on the environment and human health. To mitigate this issue, a complex system dynamics (SD) model is imperative to holistically analyse different transition pathways and their impacts on the collection and recovery outcomes. However, there is a significant challenge in communicating such a model to stakeholders. A systems model can be highly politicised by stakeholders where entrenched opposing opinions can lead to a rejection of the ideas and logic presented in the model. Stakeholders often do not possess the necessary skills to understand a complex mathematical model.

Serious games can overcome this challenge by simplifying a complex model via a user-friendly interface. It offers stakeholders a safe environment to experiment with different types of decisions and reflect on the outcomes. A well-designed intervention-based serious game can bridge between science and practical decision-making activities as well as conveying real-world system complexities. van Hardeveld, et al. [6] argued that serious games can support collaborative management strategies, improve understanding, and enhance cooperation among stakeholders.

In this paper, a serious game called *R3SOLVE* was designed from a previously developed SD model. The SD model focused on examining different transition pathways considering the complex interactions between PV adoption, waste generation and recovery, as well as strategies and policies by different stakeholders. The game architecture consisted of a knowledge elicitation engine (KEE) (i.e. SD model and game database) as the decision support system for the game and user interface that are connected through communication controller, the multiplayer controller plugin, events controller, and simulation and decision controller.

The goal of the game is to achieve certain collection and recovery outcomes through a mix of decisions ranging from product stewardship strategies, landfill regulation, technological investment, promotional effort, reuse strategy, and infrastructure improvement. The game has a single player mode where a player can access all decisions and a multiplayer (turn-based) mode where two players with different roles working collaboratively to achieve the desired outcome. Rewards and penalties also exist in the game to promote players' extrinsic motivation to use critical thinking.

Both game mode has been tested in separate workshops to identify bugs and issues regarding goal clarity and in-game information. A preliminary evaluation on the game perceptions as well as players' cognitive and relational learning (den Haan et al., 2020) indicates that the game is positively received and is successful in improving stakeholders' decision-making ability.

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Keywords: *Photovoltaic, solar panels, waste management, circular economy, serious games*

EXTENDED ABSTRACT ONLY

Agile, antifragile, AI-enabled command and control: The dynamics of survival in high-intensity conflicts

J.M. Simpson and **S. Elsawah** [a]

[a]*School of Engineering and Information Technology, UNSW-Canberra, ACT, Australia.*
Email: jacob.simpson@student.unsw.edu.au

Abstract: The complexity induced by multi-domain operations in future conflicts calls for new concept of operations (CONOPs). These CONOPS need to be designed to account for the complex interdependent effect space that current and future disruptive technologies, such as Artificial Intelligence (AI) and Autonomy, bring. The recently developed A3IC2 (Simpson et al., 2021) concept brings AI and autonomy into the Command, Control, Communication, Computing, Cyber, Intelligence, Surveillance, and Reconnaissance (C5ISR) sphere to create a responsive system-of-system in highly dynamic C5ISR for multi-domain (Air, Land, Sea, Space, and Cyber) operations. The A3IC2 concept integrates AI into C5ISR systems as a means to minimise the risk of automated decision-making in complex strategic environments in order to effectively support multi-domain operations.

A3IC2 is distinct from the current consensus within strategic studies on what constitutes an ideal system to survive and win during war. Traditionally, C2 systems have been argued to benefit from a strategy that focuses on maximising 'agility' within a complex competitive environment (Alberts, 2011; Oosthuizen and Pretorius, 2015; Jensen, 2012; Berggren et al., 2014). However, an antifragile system is able to learn from stress, shocks and volatility, enabling the ADF, as a system-of-systems, to improve itself over time through overcompensation (Taleb, 2012). The successful application of this strategy within C2 organisations will permit the ADF to enhance its capabilities to deter and shape the operational environment via rapidly learning to overcompensate from the volatility and shocks of high intensity, near-peer conflict.

In order to validate the A3IC2 strategy, this paper will conduct a System Dynamics (SD) analysis on how antifragile elements can be implemented to improve ADF C2 systems. It will contribute to existing knowledge in the field of SD on C2 systems through the comparison of agile and antifragile C2 s ystems. It will produce a unique perspective on the topic through specific policy recommendations to improve antifragility dynamics within ADF C2 systems. The SD approach will demonstrate how A3IC2 functions as a system holistically, enabling the discovery of important variables, the effect of changes in policy on the emergent performance of the system, and what the ideal measure of performance is to assess an antifragile C2 system. A stock and flow simulation will be produced to clearly demonstrate the structure of a agile and antifgragile C2 systems, encouraging senior ADF military officers to challenge their own mental models of what constitutes an effective C2 system and how best to design one for the ADF.

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Keywords: *Strategic studies, system dynamics, antifragility, command and control, A3IC2*

Military asset management and resource planning with system dynamics and optimization

Hasan Hüseyin Turan[a] and **Sondoss Elsawah**[a]

[a]*Capability Systems Centre, University of New South Wales, Canberra, Australia*
Email: *h.turan@adfa.edu.au*

Abstract: This research focuses on the important topic of strategic decision-making in the area of military asset and resource planning. This topic is crucial for the present and future of defence-force operational readiness. A wide range of decision problems such as fleet size and mix, workforce planning, maintenance, facility location, and life-cycle analysis are covered in the asset management and planning as depicted in Figure 1.

Military asset and resource planning can be viewed as an unstructured, complex, and dynamic problem, as it exhibits several challenging features (e.g., path-dependence, dynamic complexity, and tightly coupled subsystems) for decision making (Turan et al., 2020). System dynamics (SD), a systems modeling and simulation methodology, is well-suited to deal with mentioned challenges due to its capability of capturing the feedback inter-dependencies between different parts of the strategy (Kunc & Morecroft, 2009). In this research, a large-scale SD simulation model is built to cover and address the different aspects of asset management in the military. The stand-alone use of the model allows users to examine the performance of a strategy over time from both holistic and lifecycle viewpoints.

Figure 1. The class of decision problems covered in asset management and planning.

Nevertheless, the developed SD model like any other simulation model neither suggests nor seeks the best/optimal strategy(ies). To alleviate the shortcomings of the SD model, we couple optimization algorithms (mostly metaheuristics including genetic algorithm and simulated annealing) with the developed SD, which is known as simulation-based optimization, to effectively search a very large set of feasible decision space to find optimal asset management strategies.

To test the applicability of the approach a real case study is used, which is motivated by the recent modernization efforts of the Australian Defence Force. The results obtained indicate that this approach leads to a considerable increase in operational readiness and identifies the causes of inferior performance.

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Keywords: *Asset management, system dynamics, military, metaheuristics, simulation-based optimization*

Closed-loop stochastic simulation: determining the number of replications and anomaly detection in the output metrics

Lisa Blumson [a] and **Belinda Chiera** [b]

[a] *Defence Science and Technology Group, PO Box 1500, Edinburgh, SA, 5111*
[b] *UniSA STEM, University of South Australia, Adelaide SA 5000*
Email: lisa.blumson@dst.defence.gov.au

Abstract: Closed-loop stochastic simulation analyses provide a practical, powerful mechanism for performing experimental studies across a broad range of applications with varying levels of complexity. However, simulation studies can be computationally expensive in practice, with several independent replications required to capture the underlying stochastic nature of the simulated events. Determining the exact number of simulation replicates required is thus a critical aspect of the simulation design. Too few replicates may not adequately capture the underlying nature of the simulated variables of interest, compromising the validity and accuracy of conclusions drawn on the basis of the simulation. Conversely, studies which perform too many replications have an unnecessarily large, expensive computational overhead.

A further challenge in stochastic simulation studies lies in the identification and classification of outlying, anomalous values in the multivariate simulation output data. Outlying observations may arise from a number of sources due to the stochastic nature of the simulations, including the occurrence of unexpected events, or sequences of events, within the simulations or the way in which simulation behaviours are coded for the specific scenario under consideration. Detecting and appropriately handling anomalous observations is a key step to ensure the validity and veracity of subsequent analyses and decisions made on the basis of the simulation.

In this presentation, two new tools will be presented to address these challenges in stochastic simulation studies, namely (1) the Study into the Number of Replications for Experimentation (SNORE), and (2) the Simulation Pattern Recognition and Outlier Classification for Key Events Tool (SPROCKET) tools.

SNORE provides a robust, reliable and accountable method for determining the number of simulation replications required for stochastic simulation studies. The tool is structured to estimate the minimum number of replications required such that a user-specified level of tolerable error is simultaneously satisfied for each of the multivariate simulation output performance metrics. Additionally, SNORE supports flexible error targets that can be uniquely defined for each individual metric and requires only an initial batch of n simulation replications to perform the calculations. It is generally recommended that n be at least 30 replications, with the results of SNORE typically stabilising at approximately 50 replications. Within SNORE, separate consideration is provided for the different data types of multivariate output metrics from the stochastic simulation, namely continuous, binary and discrete.

SPROCKET is a demonstrably effective tool for detecting outliers in the simulation output data, in both the multivariate performance metrics as well as at the level of individual events within each simulation replication. SPROCKET can also be applied as a useful diagnostic tool for verifying the integrity of the coded simulation behaviours to ensure the simulation is performing as intended and expected. SPROCKET for multivariate data has been developed on the basis of several existing high-performing anomaly detection methods, including robust variants of the Mahalanobis distance, k-nearest neighbour methods, the Local Outlier Factor and Histogram-Based Outlier Score methods. SPROCKET is a score-based approach to outlier detection, with each replication in the simulation assigned a score representing the degree to which that replication is anomalous in the context of the entire dataset for the simulated scenario under consideration. Scores are then aggregated between methods using a weighted arithmetic mean to produce the final outlier score for each replication.

Application of SNORE and SPROCKET in simulation design and output analysis is expected to provide a robust, reliable support for decision-making on the basis of the simulated events.

Keywords: *Anomaly detection, stochastic simulation, number of replications*

Factor screening for binary responses from combat simulations

H. Demirhan [a], **S. Georgiou** [a], **A. Gill** [b] **and S. Stylianou** [a]

[a] *School of Science, Royal Melbourne Institute of Technology, Melbourne, VIC 3001, Australia*
[b] *Defence Science and Technology Group, PO Box 1500, Third Avenue, Edinburgh, SA 5111, Australia*
Email: andrew.gill@dst.defence.gov.au

Abstract: Combat simulations are an increasingly important tool for analysts in developing advice to Defence decision-makers around military capability, by providing an alternative to physical trials and military exercises where it may be unsafe or prohibitively expensive to operate. Anecdotally, high-fidelity simulations often follow the Pareto principle whereby a large proportion of the output is governed by a small proportion of the inputs. Thus, screening for the 'critical few from the trivially many' prior to meta-model construction is a prudent first step. Somewhat surprisingly, our literature search for binary response simulation factor screening only produced the thesis by Li (2011).

In this paper we analytically critique the hybrid screening method of Li (2011) before arguing that the original approach of Shen et al. (2010) for continuous responses can still be utilised for binary responses. A comparison of the numerical effectiveness of an apparently D-optimal design proposed by Yang et al. (2011) with a traditional factorial is performed, before exploring the sensitivity of the original Shen et al. (2010) approach to its user-specified parameters.

We show that the requirement of the modified approach of Li (2011) in using the sample covariance matrix of the regression estimates makes it susceptible to singularity issues due to rank deficiency. In contrast, we note that the critical point in the applicability of the original Shen et al. (2010) technique is the normality of the model parameters, which can follow from either the normality of the data or, importantly, any other asymptotic property of the estimation method used for model fitting. As the maximum likelihood estimates of parameters of the logistic regression model follow an asymptotically normal distribution, the Shen and Wan (2009) approach remains appropriate. We note that there is no need to assume normality of log-odds ratios such as made by Li (2011).

Numerical experiments found that the original Shen et al. (2010) method can work well when the required parameters are specified correctly. It worked efficiently with both the typical fractional factorial design and the alternative D-optimal design specifically for binary responses. As expected the D-optimal design outperforms the fractional factorial design, but the differences were relatively minor and the method seemed to behave well under both designs.

The correct specification of the user parameters is related to the problem being studied, but is influenced by parameters not under the researcher's control, for example the correct assumption of the fitted model and the identification of the variability of the true active/inactive coefficients. The method was not found to be robust to misspecification of these user parameters and the results in such cases might be misleading at best. This disadvantage makes its use highly problematic in practical situations where prior knowledge of the true underling model and range of significant/insignificant coefficients might be limited.

Further research is thus required in identifying a robust factor screening method for binary responses from stochastic simulations. Similarly, for response variables that are discrete but bounded, such as the number of combat assets lost or remaining, an effective screening approach remains elusive. Such generalisations are not straightforward and more research is needed in these directions.

Keywords: *Logistic regression, Fractional factorial design, D-optimal design, simulations, screening procedures*

Regression-based approaches for simulation meta-modelling in the presence of heterogeneity and correlation

L. P. D. M. Garces [a], **T. Bogomolov** [a], **and B. A. Chiera** [a]

[a] *UniSA STEM, University of South Australia, Adelaide, South Australia, 5000*

Email: len_patrick_dominic.garces@mymail.unisa.edu.au

Abstract: We discuss several regression-based methods for simulation meta-modelling and illustrate these methods using combat simulator data. Since the use of common random numbers (CRNs) as a variance reduction technique induces correlations in the outputs generated by different simulation inputs, it is crucial to accommodate the possibility of heterogeneity, heteroskedasticity, and correlation when building meta-models. Furthermore, mainstream combat simulators produces a variety of output types, including continuous, binary, and count data. While extensive work has been done towards the development of simulation meta-modelling methods for continuous outputs, the meta-modelling of discrete, binary, and count data seems to be less understood.

To this end, we consider the use of estimated generalized least squares (EGLS), finite mixture generalized linear models (GLMs), and heteroskedastic binary regression, which specifically incorporate correlation, heteroskedasticity, and heterogeneity, for meta-modelling with continuous, binary, and count output data. EGLS extends the ordinary least squares (OLS) model by allowing the errors to have a non-diagonal covariance matrix. Finite mixture GLMs capture the possible heterogeneity in regression intercepts and slopes due to the possible existence of latent clusters in the simulation inputs. Heteroskedastic binary regression is a latent variable approach for binary data which jointly models the conditional mean and the scale parameter of the distribution of the latent error term.

An analysis of combat simulator data using the aforementioned methods shows that there is significant heterogeneity in the base mean levels and in the marginal effects of individual input variables for continuous and binary output data. Furthermore, likelihood ratio tests suggest an improved fit to the data when using heteroskedastic probit and logistic regression models over their homoskedastic counterparts. However, the analysis of count output data points to severe underdispersion in the data rather than heterogeneity in the sense of the finite mixture GLMs. This also suggests that approaches which jointly model the mean and dispersion may be viable alternatives.

Keywords: *Simulation meta-modelling, common random numbers, estimated generalized least squares, finite mixture generalized linear models, heteroskedastic binary regression*

Heteroscedasticity and correlation in linear regression

A. Gill [a]

[a] *Joint and Operations Analysis Division, Defence Science and Technology Group, Australia*
Email: andrew.gill@dst.defence.gov.au

Abstract: At the last MODSIM conference I illustrated two common pitfalls that may present themselves during the design and analysis of simulation experiments (Gill 2019). The first provided good reason to seek and employ orthogonal designs, such as two-level fractional factorials or orthogonal Latin Hypercubes (Montgomery (2012) provides a good introduction). The second pitfall belies the analysis of simulation experiments and the potential dangers of making the common *independent and identically distributed* (iid) assumptions on the regression residuals. Such assumptions allow the classic *Analysis of Variance* (ANOVA) statistical procedures to be employed, as taught in statistical texts such as Montgomery (2012) and others, and are often standard on statistical software (e.g., Minitab and JMP). However, in simulation experiments the assumption of *identically distributed* responses at each design point is often not met in practice. In fact, heteroscedasticity is more often the norm and Law (2007) provides examples where the variances can differ by an order of magnitude or more, and while our control over the assignment of the *pseudo-random number* (PRN) streams within simulations does allow us to ensure independent responses at all design points, the use of *common random numbers* (CRNs) is increasingly popular, as it is helpful in the debugging phase of scenario development.

In Gill (2019) I used a numerical experiment with a stochastic simulation (JFORCE, see Au et al. (2018)) to illustrate how the precision (variance) associated with linear regression coefficients can differ if iid is assumed, and the subsequent possibility of making incorrect inferences such as false negatives (declaring a factor as unimportant when it isn't) as a result. However, that paper necessarily skipped over much of the underpinning statistical and mathematical derivations. It also alluded to, but did not expand upon, an alternative motive for employing CRNs, as a *variance reduction technique* (VRT) similar to the use of blocking in physical experiments, which practitioners may be unaware of.

The intent of this paper is to fill those gaps. Purely for ease of exposition purposes, it will use very simple linear regressions (one or two factors) to enable derivations of various regression coefficient confidence interval constructions, as well as to illustrate how the assignment of PRNs might be exploited to our (analytical) advantage. Doing so will clearly illustrate how heteroscedasticity and dependence can influence linear regression analysis. Seminal references, though perhaps less well-known nowadays, on how these simple illustrations generalise to more practical multiple linear regression problems will then be described.

Construction of *confidence intervals* (CIs) for linear regression modelling is a key element of simulation analytics, to test the statistical significance of the influential factors and to bound their magnitude. However, too often the simplifying assumptions of iid residuals are used in statistical texts and/or software. This paper hopes to persuade the reader that such assumptions need not be made, and by reintroducing the work of Scheffé (1959) provide the mathematical background to procedures in the general case. In particular, the notion that independence of the simulation response to a designed experiment is a virtue, is hopefully dispelled. Indeed, the unique ability to control simulation's randomness should instead be viewed as an opportunity, to increase the precision of the linear regression CIs. The seminal work of Schruben & Margolin (1978) provides the optimal strategy of assigning the PRN streams for this goal.

Future research will focus on two extensions. First, while factorial designs are known to be optimal for multivariate linear regression when iid assumptions are met, the presence of heteroscedasticity has been shown to require the search for an alternative optimal design (Atkinson & Cook 1995). Second, for simulation responses that are not continuous (e.g., binary or count), *generalised linear regression* is used, and it is not clear that the assignment strategy of Schruben & Margolin (1978) will automatically apply. I hope to share the outcomes from this research at MODSIM 2023.

Keywords: *Multivariate linear regression, Variance reduction, Heteroscedasticity, Confidence ellipsoid*

EXTENDED ABSTRACT ONLY

Comparing experimental designs using an anti-ship missile defence exemplar

P. van Bodegom [a], **P. Mellen** [a] **and T. Do** [a]

[a] *DSTG Edinburgh, Weapons and Combat Systems Division*
Email: patrick.vanbodegom@dst.defence.gov.au

Abstract: The Australian Government identified in the 2016 Defence White Paper that 'the quality and quantity of cruise and short and medium range ballistic missile forces in the Indo-Pacific is rising'. In response to this proliferation of missile technology, there is significant interest in enhancing maritime air and missile defence capability to protect Australian deployed forces. As outlined in the 2020 Force Structure Plan, this includes a significant investment into autonomous systems for a range of missions, including the use of uninhabited aerial systems (UAS) for enhancing situational awareness in the maritime environment.

The role of UASs in anti-ship missile defence (ASMD) can be explored using modelling and simulation. Improvements in defensive performance can be evaluated by simulating a range of UAS concepts operating in concert with other platforms. However, as the parameter-space grows, or the models representing real-world systems become more detailed, the computational resources required to execute the simulations can potentially increases beyond feasibility. Design of Experiments offers a structured process of extracting information from an experiment using a minimal amount of resources (Sanchez, et al., 2020). The purpose of this study was to screen for the most influential factors affecting missile defence performance and assess the effectiveness of the experimental designs used.

For the purpose of this research, unclassified generic models, broadly indicative of classes of systems, were used within a discrete-time, constructive, simulation environment. In this environment, the UAS provided early warning and third-party targeting for a naval surface combatant, which launched surface-to-air missiles (SAMs) to intercept an incoming anti-ship cruise missile, as illustrated in Figure 1. A range of factors were varied across the different simulations in order to assess their influence on the success of the missile defence capability. These factors included UAS altitude, range, and UAS-to-ship datalink performance. This presentation will utilise this example to explore the strengths and weaknesses of the different experimental design techniques tested within this study.

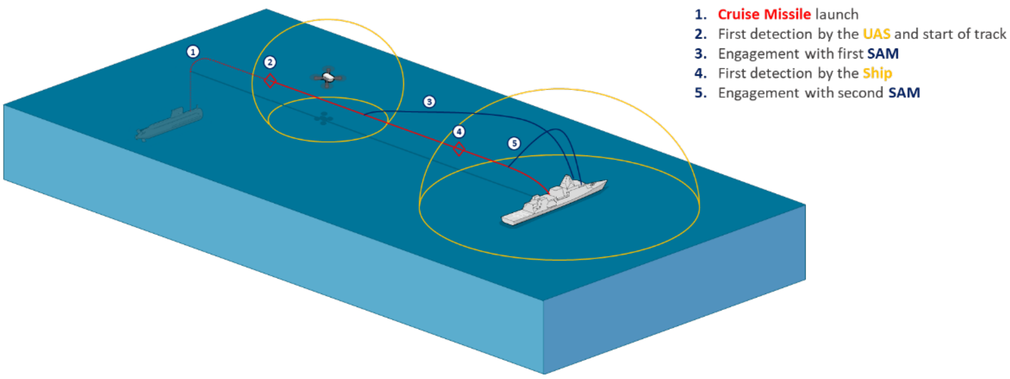

Figure 1. Uninhabited aerial system supporting a ship engaged in an anti-ship missile defence scenario.

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

EXTENDED ABSTRACT ONLY

Analysis of Australian weather data using Apache Storm

O. Grimes[1], Q.T. Trinh[1], V. Vaid[1], S. Menon[1], R. Watson[2] and P. Ryan[2]

[1]Swinburne University of Technology, Hawthorn VIC 3122, Australia
[2]Ryan Watson Consulting Pty Ltd, Vermont VIC 3133, Australia
Email: richard@ryanwatsonconsulting.com.au

Abstract: The science of weather forecasting has come a long way since the first use of scientific instruments to measure barometric pressure and other parameters in the mid-19th century. In those days reasonably accurate forecasts could be made of the next-day's weather in a relatively small region like the British Isles. In the years since then, meteorological data collection and analysis have become more sophisticated and weather forecasting has become a multi-national collaboration able to accurately forecast the weather over much of the planet up to 10 days ahead, and make longer-term predictions of wet or dry seasons. This has made a big difference in sectors like agriculture, tourism, water resources, aviation and fire prevention.

Weather data includes humidity, temperature, rainfall, radiation, wind speed, air pressure, sunlight strength, etc. and is produced in real-time. Big data analytics is the science which has been developed to handle such data and extract value and insights from it (Fathi et al 2021). Modern weather forecasting produces petabytes of data every day and professional weather forecasting utilises high performance computing systems with distributed storage. However smaller forecasting systems which can run on desktop computers can still produce valuable information. This paper describes a two-semester project carried out by a team of Swinburne University students to forecast whether fog or haze is expected in Australian capital cities based on various parameters including temperature, humidity, wind speed and air pressure.

The project used open-source software, and the Swinburne team, in consultation with the project sponsor, Ryan Watson Consulting Pty Ltd, chose to use the Apache Storm framework (Kumawat 2020). This can ingest real-time data from a variety of sources such as the Apache Kafka publish-subscribe messaging system. The Apache Cassandra No-SQL database system was also used. Apache Storm is highly scalable, fault tolerant and user-friendly, and can be used in small as well as large organisations.

The input weather data was analysed using the python machine learning library scikit-learn, with the Support Vector Machine classification algorithm the chosen option. This calculates a decision boundary, which is a hyperplane between classes which can be linear or non-linear. The classes for outputting predictions were positive haze, positive fog, or both negative haze and negative fog.

The students were required to produce the full range of project documentation including a software design and research report, quality assurance plan and test plan. The sponsor provided a virtual cloud server to enable all members of the team to access and work on project files and documents. The project met all its objectives, including the production of an app to predict the probability of fog or haze in Australian cities selected from a pull-down menu.

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***Keywords**: Weather forecasting, Big data, Apache Storm, Apache Kafka, Publish-Subscribe, Apache Cassandra*

EXTENDED ABSTRACT ONLY

Analysis of Victorian road accident environmental data

Upuli Karunaratne, Richard Watson and Peter Ryan

Ryan Watson Consulting Pty Ltd, Vermont VIC 3133, Australia
Email: richard@ryanwatsonconsulting.com.au

Abstract: Copious research has been undertaken to better understand the causes of road accidents so as to take action to mitigate their frequency and severity. Considerable data is available on road accident events and published as open data on the internet. Such data include variables relating to the accident, such as accident type: vehicle hitting stationary object, collision between vehicles, vehicle hitting pedestrian, etc; accident severity: fatal, serious injury, minor injury, property damage, etc. As well, there are many environmental variables associated with accidents such as the road type, neighbourhood infrastructure, demographics of participants, etc. These datasets are also frequently published on the internet.

Data mining is a process for investigating large datasets such as the above, often termed big data. It discovers and extracts predictable and consistent patterns as well as methodical connections among variables, and after that validates the results (Mor et al. 2021). One type of data mining is association rule mining, which aims to find statistical relationships between data, such as correlations between road accident counts per year and environmental variables for a specific region. Many studies have applied data mining to road accident analysis in various parts of the world (eg Dhanya 2021 in Bangalore, India). Some such studies have been undertaken in Australia, but there is a need for further work using the latest available data and analysis methods.

Road accident data for the state of Victoria has been published by VicRoads since 1987, and much geospatial and demographic environmental data is available from open-source platforms such as the Australian Urban Research Infrastructure Network (AURIN), Victoria's Spatial Datamart, and the City of Melbourne's open data portal. Previously the authors have used predictive machine learning to visualize and analyse Victorian road accident event data (Watson and Ryan 2020). The present study aims to use discovery techniques to establish how environmental variables, particularly geospatial, are related to accident count rates in particular areas. According to Mor et al. (2021), the process of data mining must be preceded by learning about the application domain, identifying data sources and preprocessing the data. Data mining is then used to extract patterns and identify those of interest. This presentation will review the progress achieved so far and the most appropriate analysis methods suggested by the data.

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***Keywords**: Road accident data, data mining, environmental variables, predictive machine learning*

Sentiment analysis of social survey data for the City of Casey

M. Lepelaar[1], A. Wahby[1], M. Rossouw[1], L. Nikitin[1], K. Tibble[1], P. Ryan[2] and R. Watson[2]

[1] *Swinburne University of Technology, Hawthorn, Victoria 3122, Australia*
[2] *Ryan Watson Consulting Pty Ltd, Vermont, Victoria 3133, Australia*
Email: peter@ryanwatsonconsulting.com.au

Abstract: Big Data analytics can be used by smart cities to improve the liveability, health, and wellbeing of their citizens. Smart cities and councils use social surveys and also social media to engage with their communities and these can require sophisticated analysis techniques. The primary direction of this research was focused on using a lexicon-based approach to carry out a sentiment analysis on data from social surveys to produce high-level reports of actionable insights. Data analysis techniques using RStudio were applied to open-source datasets, which included the Casey Next short survey 2016 dataset published by the City of Casey (CoC) and the 2018-20 Social Indicators Survey datasets published by the City of Melbourne (CoM). Initial findings revealed that the qualitative nature of the CoC dataset could produce rich insights using sentiment analysis, whereas the CoM datasets were not suited to this analysis due to their quantitative nature and were not analysed further. These actionable insights could be used by the CoC to compare and validate its own findings and to reveal further insights.

The 2016 Casey data was first cleansed and then RStudio analysis performed to create word cloud visualizations and bar charts for sentiment analysis of the survey questions. The analysis has led to several actionable insights for the CoC. These include that the CoC should: consider safety, cleanliness and family friendliness as their top priorities; invest further in the environment providing more parks and green spaces; and improve transport options for their residents. These findings were then used to inform social media analysis via the Twitter application programming interface (API). The Twitter API was customised to extract tweet data posted by users within a 25 km radius of the centre of CoC's geographical boundaries specific to relevant keywords, to calculate sentiment based on the most recent data.

The R codes were integrated within a Shiny application package to create a set of interactive webapps hosted through the Shiny server which produce (a) word clouds and bar charts of sentiment from the historic survey data and (b) more immediate sentiment analysis as bar charts from Twitter feeds. Due to restrictions and limitations in terms of publishing findings from the Twitter data, the webapps were embedded within a website set up through Hostinger to secure and restrict access only to approved audiences. The main purpose of the Twitter API and website is to provide a web solution that can be customised to estimate current sentiment for key issues for the CoC. The solution can be refined to increase its scalability, accuracy and performance through further development and research.

The project was carried out by a team of students from Swinburne University of Technology for the sponsor Ryan Watson Consulting Pty Ltd (www.ryanwatsonsonsulting.com.au). This project was proposed to impart valuable knowledge and skills to the students and prepare them for jobs in the rapidly growing data science market while the sponsor also planned to expand its technical skills repertoire in sentiment analytics to better serve its clients in the smart cities marketplace.

Keywords: *Smart cities, open datasets, data analytics, government, health & wellbeing, Python, RStudio*

The present and future of numerical environmental modelling

Peter Steinle [a]

[a] *Research Program, Science and Innovation Group, Bureau of Meteorology, Melbourne, 3000, Australia*
Email: peter.steinle@bom.gov.au

Abstract: Numerical models of the atmosphere, land and oceans provide our most comprehensive, physically-consistent representation of the environment, across a very large range of scales – both spatial and temporal. None-the-less a level of post-processing is still required to convert this large amount of data into user-relevant variables, remove model biases etc. This presentation will provide an overview of environmental modelling datasets currently available, and those that are expected to appear in the latter half of the decade. Some of the consequences for data-driven applications that process this data will also be discussed.

The full datasets from modern environmental models are already overly cumbersome, posing major difficulties around storage and dissemination. Models naturally will, however, continue to become increasingly complex, with most global models now coupling atmosphere, land, ice and ocean models and including some form of aerosols. Not only will the sophistication of all these components increase, but the resolution both horizontally and vertically will increase, as will the ensemble size. This growth in data does not just apply to predictive models, but also reanalyses, as can be seen by comparing the recently introduced ERA5 (https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5) with its predecessor ERA-Interim (https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era-interim). Nor does it just apply to global models, with most centres running limited area models, and some also producing regional reanalyses at scales of 1-3km such as BARRA (http://www.bom.gov.au/research/projects/reanalysis/). Meanwhile, operational centres are experimenting with global models with similar resolutions to the current limited area models and limited area models with resolutions of order 100m. There is an increasing need for information at these finer resolutions not only to improve public safety forecasts, but also because the efficiency, reliability and safety of energy and transport sectors are becoming increasingly dependent on very localized atmospheric conditions.

Currently much of the added value from post-processing systems comes from adding spatial detail; however, resolutions are being reached where not much more detail can be reliably included. With such large datasets, however, there is still considerable potential to add value to the data, by providing a more sophisticated calibration and transformation to more user-relevant quantities. In addition data-driven algorithms are also being developed to replace or optimize computationally-expensive sections within the models. None-the-less there are still many challenges in this area.

Keywords: *Numerical environmental prediction, reanalysis, big data*

OneWorld: Evolving an architecture for complex system representation in engagement simulation

R.D. Armstrong [a], **M.J. Christie** [a], **and P.R. Mellen** [a]

[a] *Weapons and Combat Systems Division, Defence Science and Technology Group, Edinburgh, South Australia*
Email: OneWorldAdmin@dst.defence.gov.au.

Abstract: The Weapons and Combat Systems Division (WCSD) within the Defence Science and Technology Group are responsible for providing advice to the Australian Defence Force (ADF) on the performance of Australian weapons systems. These weapons systems cover a range of system types including surface ships, aircraft, and ground based assets. This advice is used to inform the capability acquisition process and how those capabilities could be best employed by the ADF. WCSD has developed a range of modelling and simulation (M&S) tools in order to undertake analysis to underpin this advice. In order to streamline aspects of this development pipeline and simplify integration efforts WCSD developed a composite model architecture called OneWorld.

OneWorld was developed to describe and define a series of modelling interfaces and datatypes which could be used to integrate new models. It also provides an initial set of pre-integrated models that can be used to represent generic systems. It was created with three core design goals:

- Simplify the process of integrating new models into a simulation.
- Promote model re-use through ease of integration.
- Reduce maintenance requirements across the M&S toolset.

As the problem space being analysed by WCSD has continued to grow in scope and complexity, there has been greater demand on the M&S toolset to represent a larger number of systems with greater fidelity. OneWorld now requires major updates to ensure it can continue to support these activities into the future. Whilst ongoing development has allowed OneWorld to remain a key component of WCSD's M&S toolset there are a number of limitations with the architecture. These are becoming more pronounced as the scope and complexity of simulations increases, and as more external partners apply OneWorld to meet their own needs. Three key limitations include:

- **Flexibility.** Whilst having fixed interfaces and datatypes guarantees that any model that is using a particular OneWorld signal is sending the expected data; it limits how readily new signals can be developed as model requirements evolve.
- **Extensibility.** The well-defined interfaces guarantee interoperability between models however this does impose a restriction on model developers and can encourage users to integrate their models at higher levels in the hierarchy to avoid the constraints.
- **Scalability**. OneWorld is built to execute models within SimFramework. This currently requires the entire world to be run as a single process limiting the scale and complexity of simulations that can be supported.

Despite these limitations OneWorld provides key capability to WCSD and must be further developed to meet future requirements. In doing so WCSD, in collaboration with their partners, continue to evolve a robust M&S capability for engagement simulation that provides valuable analysis of ADF capability.

Keywords: *Integrated modelling, engagement modelling, computational simulation, modelling architecture*

Optimal location of launchers in a missile defence system

N. Azzollini [a], B. Babu [a], A. Reade [a] and J. Rodda [a]

[a]*Mathematics Clinic, UniSA STEM, University of South Australia, Mawson Lakes SA 5095*

Abstract: A commonly recognised problem in defence is defending against incoming missile threats, and determining how a variety of platforms and assets must work collaboratively in order achieve mission success.

A particular problem is the optimal placement of sensors and surface-to-air missile launchers around a high-value asset. The primary objective in this instance would be to defend the high-value asset with the greatest likelihood of success. The missile defence systems considered include sensors and missile launchers, which are used to detect and interdict enemy missiles, respectively.

Our problem is to optimise the arrangement of a sensor and missile launcher to defend a high-value asset against threats from any possible direction. We devise an objective function which measures the probability of failing to intercept at all possible intercept points across all possible paths of an incoming missile. We use a simple simulation to calculate the objective score for a given arrangement of sensors and missile launchers. We optimise the arrangement using a Nelder-Mead optimisation method, which calls the simulator with candidate arrangements. Nelder-Mead was used because it does not require derivatives, is easy to implement and can handle multidimensional non-linear optimisation.

We tested our optimiser and simulator using 6 different test cases where we optimised the missile launcher position for various threat scenarios. Some of the resulting optimal missile launcher positions were closer to the high value asset than we anticipated. We found, for example, that if the threat was entirely from one direction then the optimal missile launcher position is far from the asset it is protecting. But if even a small probability of attack, such as 0.0001, occurs from the opposite direction then the missile launcher would move back closer to the asset.

This project is supported by the Commonwealth of Australia as represented by the Defence Science and Technology Group of the Department of Defence. The work for this project was conducted as a part of the University of South Australia's Mathematics Clinic for 2021. The Mathematics Clinic is a year-long sponsored research project undertaken by final-year undergraduates studying mathematics, and offers in-depth research experience in real world mathematics where the project is posed from industry and supported by academic advisors.

Keywords: *Missile defence, facility location, optimisation*

Comet: A naval Combat Management System model for combat analysis

S.G. Blaess [a], **M.J. Christie** [a] **and J.L. Mitchell** [a]

[a] *Weapon and Combat Systems Division, Defence Science and Technology Group, Edinburgh, South Australia*
Email: simon.blaess@dst.defence.gov.au

Abstract: A Combat Management System (CMS) is the computers and software of a naval platform which integrates the sensors, weapons, displays, data and other equipment, enabling the naval platform to operate efficiently and effectively to achieve mission success. In a hostile environment where threats may be fast moving, hard to detect, large in number, or all of the above, a crewed naval surface vessel requires a CMS that not only acts at the behest of the crew, but can also act autonomously when required. The capacity of the CMS to utilise data, respond autonomously, provide information to the crew and respond to crew commands significantly impacts the ability of the platform to achieve its mission. Modelling and simulation of not just the ship's sensors and weapons, but also the CMS, is therefore critical if we aim to thoroughly evaluate the capability of the platform in combat scenarios. Such studies can reveal the strengths and weaknesses of a platform, capability gaps and areas of opportunity, providing an evidence base to improve tactics and strategy, force structure and acquisition decisions.

As of 2021, the Royal Australian Navy surface fleet includes three Hobart Class guided missile destroyers, each employing the Lockheed Martin developed Aegis CMS. The Royal Australian Navy also comprises eight Anzac Class frigates employing the Saab developed 9LV CMS. Later this decade the Anzac Class frigates will begin to be replaced by nine Hunter Class frigates with an Aegis CMS and 9LV tactical interface. Understanding the capability and limitations of these ships requires an understanding of how their respective CMS installations will perform. Based on references of the Aegis CMS, we have constructed, and continue to develop, a highly configurable CMS model called Comet, which is capable of interfacing with other models in constructive simulation environments to enable naval combat analysis studies. The architecture and functionality of Comet are presented in this paper.

Comet has been utilised in combat analysis studies to evaluate the performance of surface naval platforms against a variety of missile threats. The Find, Fix, Track, Target, Engage, Assess (F2T2EA) kill chain summarises the sequence of processes which occur in the detection, engagement and intercept of a threat. By evaluating the F2T2EA kill chain, the performance capabilities and limitations of a platform are identified and opportunities for improvement in the engagement kill chain are discovered. Alternative tactics, strategy, equipment configurations and/or new procurements can be modelled and analysed to discover if they improve capability.

Comet can be executed in two different modes: the CMS Emulation mode or the System Level Analytical Baseline (SLAB) mode. The SLAB mode is a cut-down version of the Comet Fire Control System developed to provide an efficient and comprehensive evaluation of threat engageability and interceptability at each point in time, whereas the CMS Emulation mode represents how a real CMS will engage the threat, wait for the intercept attempt to complete and then reengage if necessary. The analytical use cases of Comet are presented here in the context of analysing the air and missile defence capability of naval surface vessels.

Keywords: *Combat management system, integrated modelling, modelling and simulation, F2T2EA, missile defence*

Investigation of automation techniques and system representation for rapid analysis of missile defence scenarios

Chris Butt [a], **Ben Mashford** [a], **Kyll Schomberg** [a], **Matthew Boyall** [b] **and Glen Looby** [b]

[a] *Shoal Group, Adelaide, 5000, South Australia*
[b] *Department of Defence, Russell, 2600, Australian Capital Territory*

Abstract: The ability to rapidly iterate through scenarios of interest and undertake trade studies is becoming increasingly important as decision makers rely more on Modelling & Simulation (M&S) for cost-effective decision support. Both automation and fit-for-purpose system representation are paramount to success in this endeavour. Within Defence, Command Professional Edition (CPE) has been identified as an M&S tool which may bridge a part of the analytical spectrum between qualitative (non-M&S) analysis and detailed quantitative M&S studies which can take months or years to return results for. This work presents the initial findings of an investigation into the application of CPE to simple missile defence systems and scenarios.

For this investigation, a simplistic missile defence scenario was used comprising four main components: threat missile, defending sensor, defending interceptor, and target. The initial phase of work included investigating how each system was represented within the software. As this was not built-in functionality, to the level desired, a customised Python script was developed to extract relevant system data throughout the scenario. Scripts were used to automate the setup, execution and processing of key analytical products including Operating Areas, Defended Areas, and Missile Trajectories. It is important to note that only the in-built CPE database representations were used for this initial investigation. CPE provides means for integration of bespoke user models, hence higher-fidelity system representation, which will be investigated for future work.

Preliminary results suggest there is efficiency gained through automation techniques in providing a rapid review of the performance of a system or scenario. Positional-based automation techniques may increase the rate of answering stakeholder questions such as which areas of operation produce a successful engagement, while trajectory products allowed the analysts to better understand how accurately system performance is represented. In addition to time saved by the analyst, a key benefit to automation is consistency in the creation and presentation of the analytical product. The investigation found the representation of some systems in the missile defence scenario, that is their underlying model, was not as expected in a physical sense – and will be investigated further. An example of this was the somewhat discontinuous, and in parts linear, position versus time observed in the parabolic portion of a ballistic missile flight.

While manual analysis is possible, and often the default, establishing an automated workflow for analysis of missile defence scenarios with CPE appears to be tractable, and may greatly improve the efficiency and consistency of this work, while also providing the analyst products which can help determine the fitness-for-purpose of the underlying models.

Keywords: *Modelling, simulation, analysis, automation, command*

Exploring and assessing data visualisation techniques for simulation-based engagement analysis

T. Do [a], P. van Bodegom [a], P. Mellen [a] and W. Power [a]

Defence Science and Technology Group, Edinburgh, South Australia
Email: tho.do@dst.defence.gov.au

Abstract: Modern military engagements are highly complex scenarios with large amounts of uncertainty, and high levels of integration and interdependence between the different systems involved. In the simulations of such engagements, these complexities can result in large and complex data, particularly as the number of platforms and the fidelity of the models increase, which creates significant challenges in visualising and communicating the data. The Weapons and Combat Systems Division (WCSD) of the Australian Defence Science and Technology Group (DSTG) use a combination of physics-based and stochastic models of various fidelities in discrete-time constructive simulations to analyse and predict the outcomes of engagements for current and future Defence systems. This analysis is performed in order to inform force planning, acquisition and tactics development. This presentation will focus on two broad categories of engagement analysis data that are regularly visualised within WCSD:

i) **Large, multidimensional simulation generated datasets.** In these datasets the complexity is due to the large number of simulations. These datasets are used to develop an understanding of engagement performance across a range of scenarios, factors and levels.

ii) **In-depth simulation-based data describing complex behaviours.** In these datasets the complexity of the data is due to the intricate behaviours exhibited by the interaction of complex, composite models. Visualisation of these behaviours is used to help understand and explain the fundamental influences that drive the performance of the systems involved.

In addition, there are two major purposes of visualising data for two different audiences: i) to help analysts understand the results and the behaviours that drive them as well as identify any trends (this type of exploration is especially useful when little is known about the underlying dataset (Keim, 2002)), ii) to clearly communicate these trends and findings to the second audience, namely decision makers and external stakeholders.

Depending on the purpose and audience, different data visualisation techniques should be applied. For example, visualisations used by the analysts may be very data dense and unintuitive in order to explore all relationships between the data. This is acceptable as the analysts are likely to have a strong technical understanding of the dataset. These visualisations should help the analysts explore the dataset and identify the findings and trends. However, when externally communicating the data the visualisation should be significantly more intuitive. Additionally, these visualisations should have a very clear and intentional narrative. The analysts should be aiming to communicate a specific trend or finding to their audience, while still communicating levels of uncertainty and nuance. This is important as it facilitates better decision-making (Johnson & Sanderson, 2003).

This presentation will explore the pros and cons of a range of data visualisation and plotting techniques. Each technique will be categorised as static or dynamic, then assessed for their utility to communicate with different audiences (analysts vs decision makers) for different purposes, as well as their suitability for two major types of engagement analysis data (complex multidimensional datasets, and temporal descriptions of complex behaviours). Finally, the presentation will present proposed future research and open a discussion on data visualisation of complex, simulation-based engagement analysis.

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Keywords: *Defence, engagement analysis, data visualisation*

Reconstructing Lanchester Warfare Models Through a Lagrangian Mechanics Lens

J. Gill [a], A. Gill [b] and J. Penfold [c]

[a]*School of Physics, Adelaide University, Adelaide, South Australia, 5005*
[b]*JOAD, Defence Science and Technology Group, Edinburgh, South Australia, 5111*
[c]*JOAD, Defence Science and Technology Group, Edinburgh, South Australia, 5111*
Email: joshua.gill@student.adelaide.edu.au

Abstract: Warfare modelling is an important component of research in Defence. Even with the rise in performance of modern-day computers, simulating war is not only time-consuming but potentially obfuscates the determining factors in victory. A desirable goal of investigating warfare models is to predict the minimum force ratio required to ensure victory for one side, so-called victory conditions. Denoting the following model:

$$\dot{x} = -a(t)y, \qquad \dot{y} = -b(t)p(t,y)x, \qquad x(t=0) = x_0, \qquad y(t=0) = y_0 \tag{1}$$

as the time-dependent Generalised Ambush model, where $a(t)$ and $b(t)$ are weapon attrition rates and $p(t,y)$ determines the firing behaviour of x, Kress & MacKay (2013) studied the autonomous (time-independent) case $(a(t) = a,\ b(t) = b,\ p(t,y) = p(y))$ and derived the victory condition through the classical Lanchester (conservation) law approach. Taylor (1978, 1981) and Taylor & Brown (1983) extensively analysed the non-autonomous (time-dependent) version of Lanchester's Modern Warfare model $(p(t,y) = 1)$, however, the conservation law approach was abandoned in favour of solving for the force trajectories explicitly.

This paper investigates the idea that Lanchester warfare models could be equivalently expressed as Lagrangian mechanics problems, where the underlying symmetries might be exploited. The motivation for doing so is the observation that time-dependent conservation laws exist in such systems. In particular, a Noether symmetry will be sought to determine a conserved quantity of the system from which the victory condition can be deduced.

To recast in Lagrangian mechanics requires solving the inverse problem, that is, in finding a Lagrangian that equivalently represents the Lanchester system of equations. Fortunately, the method of Darboux (1878) provides an algorithmic procedure to compute the Lagrangian $L(t,x,\dot{x})$ associated with (1) via integration. From the various types of symmetries examined by Mei et al. (2014), the Noether symmetry was examined here, which requires finding a solution to Noether's Identity in terms of infinitesimal generators and a gauge function. If $\exists\ \xi_0(t,x,\dot{x})$, $\xi(t,x,\dot{x})$ and $G(t,x,\dot{x})$ s.t. (2a) is true, then (2b) is the corresponding conserved quantity:

$$\dot{\xi}_0 L + \xi_0 \frac{\partial L}{\partial t} + \xi \frac{\partial L}{\partial x} + \left(\dot{\xi} - \dot{x}\dot{\xi}_0\right)\frac{\partial L}{\partial \dot{x}} + \dot{G} = 0,\ Q(t,x,\dot{x}) = L\xi_0 + \frac{\partial L}{\partial \dot{x}}\left(\xi - \dot{x}\xi_0\right) + G. \tag{2a, b}$$

For Lanchester's classic modern warfare model, we demonstrate the existence of a time-dependent conservation law and conserved quantity and illustrate graphically how it reproduces the more familiar square law and force trajectory results. For two non-autonomous versions of (1), we also derive the associated Lagrangian, the form of the conserved quantity and demonstrate when $a(t) \propto b(t)$ how the Lagrangian formulation returns the equivalent victory conditions as deduced via separation of variables.

We hope that this initial exploration of reconstructing Lanchester warfare models as equivalent Lagrangian mechanics problems, and the associated search for symmetries and conserved quantities, may open up a fruitful path towards deriving analytic victory conditions for a range of time-dependent models.

Keywords: *Lanchester model, Lagrangian mechanics, Noether symmetry, conserved quantity*

The Application of Goal Structuring Notation to Modelling & Simulation VV&A

Jeremy Graham [a] **and Shan Atukorala** [b]

[a, b] *Combat System Engineering Group, Saab Australia Pty Ltd, Mawson Lakes, South Australia*
Email: Jeremy.Graham@au.saabgroup.com

Abstract: When undertaking complex systems engineering projects, such as upgrades to Naval Combat Systems, modelling & simulation (M&S) can contribute to activities such as requirement verification, system/solution analysis and selection, performance analysis and assessment, trade studies, and risk reduction. For the M&S outcomes to inform decision making there needs to be confidence that the analysis results can be relied upon. Confidence is achieved by ensuring that models, simulation, data, and processes work as intended (Verification), provide what is needed (Validation), and are fit-for-purpose (Accreditation) within the context of the questions being answered. As the scope, criticality, or complexity of the systems and scenarios involved increase, this process can quickly become overwhelming and time consuming. It becomes necessary to focus VV&A efforts only where needed.

A traditional approach of rigorous testing and review, supported by a hierarchy of checklists, is often applied at the same level to all items, based on and supporting classical engineering processes; however, much of it is not directly relevant to answering the current M&S questions and providing the desired outcomes. Gathering and checking all of the required artefacts and information to support VV&A is time consuming, cumbersome and inefficient. Additionally, the VV&A argument supporting the M&S outcomes is often captured descriptively as part of a final report, often with no formal structure to the overall argument. As such, getting stakeholder buy-in and acceptance of the argument and outcomes can be difficult, particularly late in the task.

Having utilized the more traditional approach for previous M&S tasks, a more effective, efficient, and dynamic approach to M&S VV&A was needed for subsequent tasks. An approach based on Claim, Argument, Evidence (CAE) rather than plan, test and review has since been implemented. This constrains the VV&A efforts to the desired outcomes by identifying the top-level claims to be addressed by the M&S program, capturing and agreeing to the intended argument with stakeholders, and identifying the specific evidence required to support the claims. Throughout the project, the evidence is gathered and the argument formulated and concluded progressively to support the claims, before the final argument and outcomes are captured and communicated. A tool widely used to support safety case and legal arguments is Goal Structuring Notation (GSN), which the Simulation Interoperability Standards Organization (SISO) now supports for use in the VV&A of models and simulations along with the CAE approach.

The GSN Community Standard is a graphical notation that provides a structured approach to formulating and communicating arguments. GSN identifies the claims as goals, and breaks down the argument as a hierarchy of goals and strategies until the required evidence has been identified. This focusses the development, testing and review of evidence to that which is necessary and sufficient to support the argument. As evidence items are completed, the goal hierarchy gradually becomes more complete, making ongoing progress visible. This has proven to be a valuable tool for defining, communicating, agreeing, and providing status of the argument in support of the claims, from definition and agreement of the argument up-front, to status throughout the task, and to acceptance of the final outcomes. The argument is presented hierarchically and is easy to follow and understand. Elements of the GSN can be adjusted or re-used as project needs change, to support subsequent phases of the project, or to answer additional or specific questions.

The use of a CAE approach to the VV&A of M&S places the focus on the argument rather than artefacts. The combination of CAE and GSN allows for argument and evidence supported outcomes to be agreed and understood by all stakeholders early in the project lifecycle. Project progress transparency and feedback are paramount throughout the task (e.g. at project milestones and working groups) ensuring stakeholder awareness and acceptance of modifications as the project progresses. We propose that CAE/GSN bolsters collaboration, transparency, and stakeholder engagement over standard VV&A methodologies.

Keywords: *Goal structuring notation, VV&A, modelling and simulation*

Command Professional Edition: Initial insights of a commercial military operational modelling and simulation tool

S. Hagley, E. H. S. Lo, P. J. Hoek, A. Donohoo, and J. Peacock

Defence Science and Technology Group, Department of Defence
Email: james.peacock@dst.defence.gov.au

Abstract: Computer modelling and simulation can support decision making for military organisations. Command: Professional Edition (Command PE) is a commercially available software package that models military warfighting scenarios at the operational-tactical level of resolution. Its strength as an analytical tool is the ability to "drag and drop" entities (military platforms, radars, air bases, etc.) into scenarios, customise loadouts (e.g. weapon mixes on fighter aircraft) and modify the existing database (which already contains over 11,000 platforms) with experiment specific data. The use of Command PE as a human-in-the-loop war gaming tool is its primary purpose and has been documented elsewhere. But, the implementation of its Monte Carlo features to perform simulation experiments has not been examined. This paper aims to report an exemplar analysis using a vignette from a historical warfighting scenario to assess how Command PE could be leveraged to support simulation experiments.

We examined the effect of different weapon loadouts on an air task group as it attacked a naval task group. The scenario employed was a replication from the Falklands War. Four Argentinian fighter aircraft attacked two United Kingdom (UK) ships. Historically, both ships were struck by bombs from Argentinian aircraft and one ship was destroyed. The Monte Carlo tool in Command PE was implemented by creating two scenario files to represent the different design points for the experiment (six vs eight bombs for the second Argentinian air task group). One hundred iterations per design point were captured. Various statistical tests identified the number of bombs available increased the chance of any UK ships being destroyed (31% to 58%) but had a negligible effect on the chance of any Argentinian aircraft being destroyed (84% to 87%).

Users that intend to run experiments (both simulation and human in the loop experiments) with their own data sources must have an understanding of the adjudication system within Command PE. This will enable users to incorporate experiment specific data by modifying the Command PE database (noting its defined schema) to appropriately model the warfighting scenarios. For example, some Command PE adjudication is based on probabilities that are defined within the database. Effectors, such as guided missiles, have a base probability of hit that is modified according to the platform it is targeting. In our scenario, the probability of hit for UK surface-to-air missiles on Argentinian aircraft was modified by speed, agility, altitude, angle of flight, and platform shape. These parameters were explicitly represented in the database, and incorporating experiment specific data for guided missiles must adhere to this schema. Users should also consider verification and validation of Command PE simulation outputs with appropriate, authoritative models and datasets.

Command PE can be used to perform simulation experiments that have a small number of design points. Our implementation of Command PE to perform simulation experiments is not recommended when a high number of design points are required. This is due to the approach we implemented whereby individual scenario files were manually created for each design point. Further, there is a lack of any ability to implement common random numbers. While Command PE is very much a human-in-the-loop proposition, it can be used for closed-loop quantitative analysis. But the ability to perform factorial simulation experiments with a high number of factors requires further work. There are other avenues that might be leveraged to execute a high factor simulation experiment with Command PE, including using the underlying Lua scripting.

Keywords: *Modelling and simulation, war gaming, design of experiments, data analysis, military strategy*

Strongly Connected Components for Modelling of Communications

J. Harms [a] **and A. Khan** [a]

[a] *Joint and Operations Analysis Division, Defence Science and Technology Group, Australia*
Email: jonathon.harms@dst.defence.gov.au

Abstract: Modelling platform communication capabilities is essential for accurate analysis of the interactions between multiple entities acting in a distributed manner, such as in complex military scenarios where the effects of data fusion need to be included. Modelling a distributed network requires identifying valid communication links between nodes and determining how information can be transferred across the network. Each node may be on multiple networks and there are often gateway nodes where information can be shared between networks. One approach for establishing the communication network is to test the direct link between every node. This works well with networks that have a small number of nodes and a limited number of links. However, when the network has many nodes and links the number of tests increases exponentially resulting in a dramatic increase in the computational time required to establish the network model.

This paper examines the case where there are N nodes that can communicate with every other node on multiple networks, and the connectivity is high meaning the number of links approximates N^2. Each node also has M packets of data that needs to be shared with all other nodes where a valid communication link exists at a predefined update rate. Each node aims to establish a common information baseline by comparing each received information packet with the information database already on the node and updating it with new information. In a military context, this is useful for modelling the data fusion process that is present on modern platforms. This is a computationally expensive operation. The basic approach would have a computational cost of $O(N^2 \times M)$ for the merge operations (or $\approx$ 1 million merges every update for $N = M = 100$).

The goal of this research is to establish an efficient approach for mapping the communications structure and to group nodes that have valid communication pathways. The data merging process would then be performed for each group in one operation. This paper will outline a solution based on Strongly Connected Components (SCCs) graph theory. The scenario can be modelled as a bidirectional graph which represents the distributed network. A set of nodes within a graph is an SCC if every node in that set is reachable from every other node in that set (Cormen et al. (2009)).

The computational cost of this process depends on the data structure and the algorithm that is used. An adjacency list data structure and Tarjan's Algorithm for finding SCCs were found to be the most appropriate for this application. If the graph has N nodes and E edges then the computational cost of creating and storing the graph is $O(N + E)$ when using an adjacency list (Cormen et al. (2009)). Tarjan's Algorithm can find the SCCs also with computational cost of $O(N + E)$ (Tarjan (1971)). In the worst case, with a highly connected graph where $E \approx N^2$ this results in a complexity of $O(N^2)$ to find the SCCs.

If there are K SCCs found, the number of merges will be $\sum_0^{K-1} N_i \times M$ where N_i is the number of platforms in SCC_i. Therefore, in the worst case, the overall complexity is $O(N^2 + N \times M)$. Compared to the previous $O(N^3)$ this is a significant reduction in time complexity. For a complex scenario with $N \approx 100$ a 90% reduction in total computation time from approximately 480 minutes down to 30 minutes was achieved. The outcome of this study was that significant efficiencies can be achieved using SCCs for modelling distributed networks and merging information across network nodes as compared to the approach of testing each link between nodes individually.

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Keywords: *Communications, strongly connected components, Tarjan*

A strategy for using cooperating missiles for missile defence

M. Kapsis [a], **P. Pudney** [a], **J. Aarao** [a], **W. Miller** [b] **and G. Freebairn** [b]

[a]*University of South Australia, GPO BOX 2471, Adelaide, South Australia, 5001*
[b]*DST Group, PO BOX 1500, Edinburgh, South Australia, 5111*
Email: maria.kapsis@mymail.unisa.edu.au

Abstract: We are interested in exploring the concept of using a team of low-cost defending missiles instead of a single high-cost defending missile to intercept a high-performance incoming missile. The low-cost defending missiles will have reduced seeker performance or reduced range or manoeuvrability compared to a high-cost defending missile, but will cooperate with each other to seek and intercept the incoming missile.

This paper presents a cooperative control strategy for a team of cooperating defending missiles. The objective is to minimise the probability of missing the incoming missile.

We formulate a method to predict possible paths of the incoming missile from a known initial state to a known target, and introduce the concepts of a seek region and intercept region that can be used to determine points for the defending missiles to aim towards before operating their on-board seekers. These *aim points* are placed such that the defenders are able to maximise their coverage of the seek and intercept regions within the incoming missile's manoeuvrability range. We demonstrate a simple method for calculating aim points with a couple of examples.

Keywords: *Cooperative control, team defence, air missile defence systems*

Integrating and automating a closed loop simulation capability to enable easier exploration of the parameter space

S. Kiparoglou[a] **and D. Coppola**[b]

[a]Defence Science and Technology Group, [b]Consilium Technology
Email: Stefanos.kiparoglou3@dst.defence.gov.au

Abstract: This paper discusses the implementation of the integration and automation of an analytical simulation capability that consists largely of multiple top level components and user modified tools. These disparate tools create configuration burdens and limit the exploration capability of the wider system to answer a complex question as part of a larger problem. The aim of this project is to develop a capability to explore a wide set of performance characteristics and configurations within a complex simulation environment and perform multiple forms of analysis with little to no human intervention. This is achieved by using a microservice design that can encapsulate the closed loop simulation experiment lifecycle and provide the study lead with a simple way to generate and execute a simulation, extract metrics, perform analysis and provide meaningful insights. The design will take significant steps towards allowing the study lead and associated analysts to focus more on experimental design, verification, validation and sensitivity of data but also introduce new capability options in terms of execution and analysis.

Keywords: *Integration, simulation, automation, parameters, data*

Bayesian parameter identification and coefficient estimation in combat models

Robert K. Niven [a]

[a] *School of Engineering and Information Technology, The University of New South Wales, Canberra, Australia*
Email: r.niven@adfa.edu.au

Abstract: For over a century, models of combat between opposing military forces have been used to assess attrition rates and different military strategies, starting from the simple model of Lanchester (1916). Recently, this has been extended to incorporate the logistic growth properties of ecological predator-prey models, combat between multiple combatants, and interactions with a host population (e.g., Kress et al. 2018, McLennan-Smith et al. 2019). A synthesis of such models for n forces can be written as:

$$\frac{dx_i(t)}{dt} = r_i x_i(t)\left(1 - \frac{x_i(t)}{K_i}\right) - \kappa_i x_i(t) - \sum_{j=1, j\neq i}^{n} F_{ji} x_j(t), \qquad \forall i \tag{1}$$

where r_i are recruitment rates, K_i are carrying capacities, κ_i are intrinsic decay rates and F_{ji} are functional response or attrition coefficients. A variant of (1) was given by McLennan-Smith et al. (2019) for two opposing forces and a host population, based on functionally-dependent coefficients. In keeping with related ecological models, such systems can display oscillatory or chaotic behaviour under specific conditions.

In this study, we apply Bayesian inference to time-series combat data generated using (1), to identify the important parameters and estimate their coefficients. In this method, the connection between the time-series matrices of the derivatives $\dot{\boldsymbol{X}}$ and populations $\boldsymbol{X}$ is represented by $\dot{\boldsymbol{X}} = \boldsymbol{\Theta}(\boldsymbol{X})\boldsymbol{\Xi} + \boldsymbol{\epsilon}$, where $\boldsymbol{\Theta}$ is a matrix of alphabet functions applied to $\boldsymbol{X}$, $\boldsymbol{\Xi}$ is a matrix of coefficient values and $\boldsymbol{\epsilon}$ is a noise vector. To estimate $\boldsymbol{\Xi}$, we write Bayes' rule for the posterior $p(\boldsymbol{\Xi}|\dot{\boldsymbol{X}}) \propto p(\dot{\boldsymbol{X}}|\boldsymbol{\Xi})p(\boldsymbol{\Xi})$. It can be shown that the maximum a posteriori (MAP) Bayesian estimate of $\boldsymbol{\Xi}$, assuming Gaussian noise and likelihood functions, is obtained by minimisation of the objective function (Niven et al 2019):

$$J(\boldsymbol{\Xi}) = ||\dot{\boldsymbol{X}} - \boldsymbol{\Theta}(\boldsymbol{X})\boldsymbol{\Xi}||_2^2 + \lambda||\boldsymbol{\Xi}||_2^2 \tag{2}$$

where $||\cdot||_2^2$ is the squared L_2 norm and λ is a regularization parameter.

The above Bayesian inverse method is demonstrated by application to several forms of (1) with added noise and/or missing data. Firstly, applying the above sparsification method and different information criteria to the data, we rank the model parameters formed from the alphabet, expressed as a function of the information cost of the model. This provides a mathematical formulation of "Occam's Razor", to preferentially select simpler models. It is shown that several variants of (1) are feasible. However, the model of McLennan-Smith et al. (2019) with its embedded functional dependencies has a high information cost, and is therefore impracticable. Secondly, we estimate the coefficients of the selected parameters in the presence of noise or other influences. Thirdly, we also quantify the uncertainty of each coefficient, by extraction from the posterior $p(\boldsymbol{\Xi}|\dot{\boldsymbol{X}})$. The analyses demonstrate the utility of the Bayesian apparatus for combat model validation and calibration.

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Keywords: *Combat models, Bayesian inference, parameter identification, coefficient estimation*

Verification, validation, and accreditation for models and simulations in the Australian Defence context

Kerryn Owen[1] **and Ripon K. Chakrabortty**[2]

[1-2] School of Engineering & Information Technology, UNSW Canberra, ACT 2612, Australia
[1] Defence Science and Technology Group, Edinburgh, SA 5111, Australia
Email: [1]k.owen@student.unsw.edu.au; [2]r.chakrabortty@adfa.edu.au

Abstract: Building simulation models that are valid and credible is an enduring challenge in the Australian Defence Organisation (ADO) context. Combat simulation and computer-assisted wargaming are used extensively across the Australian Department of Defence, with $1bn-2bn of investment in simulation and collective training in the Integrated Investment Plan, and simulation enabled analysis for acquisition highlighted in the Defence Science and Technology Strategy. Therefore, several billion dollars of capability, the lives of Australian combatants, and defence mission outcomes rely on the validity of such simulations.

Establishing validity and credibility can be achieved through the rigorous use of appropriate Verification, Validation, and Accreditation (VVA) processes. Such processes are well-known in Modelling and Simulation (M&S) practice. Australia typically leverages simulation models that are Commercial-off-the-shelf or Government-off-the-shelf; there is limited primary model development performed, and therefore VVA cannot be incorporated into a model's development life cycle. Because of this, VVA aligned with Australian requirements is either dependent on developer nation VVA activities (appropriate in some situations) or conducted with a constrained ability to make changes to the model, and often with limited access to corresponding real-world data.

A scoping review has been conducted in this study to gather insight into current VVA practice in the M&S community. The results of this review are presented in the form of charting relevant characteristics from selected references, cross-tabular associations between such characteristics, and statistical analysis to establish if such associations differ from those expected to arise from independent random characteristics. The conclusions of this review are applied to the ADO context through problem scoping tools from the soft systems methodology (SSM).

The scoping review shows that executable validation of simulation results against referent data sourced from physical experiments are the most prevalent form of VVA, with referent data from comparative models being a prevalent alternative. Furthermore, there is evident reliance on graphical comparison of data; this could be enhanced with objective data comparators, such as aggregate error measures or statistical techniques. Finally, there is an evident gap in VVA references from Australia. The SSM is used to propose an idealised solution to enhance the coordination of M&S in general, and the conduct of VVA specifically, within the ADO context. Based on the results of this work, it is recommended that M&S practitioners within the ADO might benefit from empirical methods of simulation results validation. Furthermore, it is suggested that the ADO might prioritise ways to support and enable such efforts. This would enhance the credibility and confidence of models applied in the ADO context, resulting in better M&S outcomes and greater opportunity to employ training and objective analysis in support of achieving defence strategic outcomes.

Keywords: *Verification, validation accreditation, modelling and simulation, Defence*

Towards efficient, dynamic and threat-aware path planning for combat simulation in COMBATXXI

Rowan Pivetta

Defence Science and Technology Group, Department of Defence, Edinburgh, 5111, Australia
Email: rowan.pivetta@dst.defence.gov.au

Abstract: DSTG uses a close-combat simulator COMBATXXI as an analysis tool to explore the potential impact of modifying technologies, tactics, concepts, and force structures in the context of military operations. An integral part of designing a simulated combat scenario is entity path generation. As the outcomes of simulated combat are sensitive to entity path placement, paths need to be accurately designed and programmed. Consequently, this process takes considerable time to develop. An automated path planner could significantly reduce the programming effort required to develop a scenario provided that the planner is capable of efficiently simulating tactical decision-making in the planning process.

The objective of this research was to investigate and design an automated path planner that can efficiently and reliably generate paths across rural battlespaces in COMBATXXI. The intended purpose of the automated planner is to firstly generate entity paths prior to running a simulation, then dynamically update entity paths during a simulation to changing conditions. Currently, effort has been focused on the development of a path planning framework with the capability to plan dynamically using a combination of pre-calculated and runtime COMBATXXI data. A prototype path planner has been developed with the capability of calculating the fastest and safest paths across moderately sized rural battlespaces given the mobility of an entity and enemy locations prior to simulation. Testing has provided valuable insight into the performance of the planner, highlighting the limitations and areas of improvement, especially with obtaining and utilising runtime COMBATXXI data, which is critical to formulating solutions.

The importance of designing a path planner suitable for COMBATXXI is finding the appropriate balance between battlespace terrain representation, computationally efficient path planning algorithms and a representation of cost, which is used to evaluate path options. Since the complexity of the problem comes primarily from planning over rural battlespaces, which can range into the tens of kilometres, solving this problem required a solution that implemented a combination of traditional path planning approaches.

The proposed path planner implements a two-stage approach that combines discrete graph-based and sampling-based methodologies in succession. The first stage implements the A* algorithm over a course navigation mesh of the COMBATXXI battlespace to find an initial path from the entity to a goal location. The second stage utilises an Informed Rapidly-exploring Random Tree Star planner to sample and refine a higher-quality solution around the A* path. By combining the two approaches, the proposed planner attempts to minimise the negative characteristics that either individual approach would have solving planning problems efficiently over the intended battlespaces.

Future capability developments will require integration with terrain analysis algorithms which classify and categorise information about the terrain features. This will enable the path planner to be used within a mission-based planning system enabling mission-based directives such as, ‘plan using road networks’ or ‘plan via a known feature’. With additional terrain-based and reasoning algorithms embedded within the path planner, this research will step closer to developing a complete path planner capable of automating entity paths prior to and during combat simulation.

Keywords: *Path planning, combat simulation, COMBATXXI*

INVITED PAPER

EXTENDED ABSTRACT ONLY

Introducing Australian M&S-based Engagement Performance Analysis Community

Wayne Power [a] **and Tristan Goss** [a]

[a] *Weapons and Combat Systems Division, Defence Science and Technology Group, Edinburgh, 5111, South Australia*
Email: wayne.power@dst.defence.gov.au

Abstract: Understanding and predicting the outcomes of modern military engagement scenarios is becoming increasingly complex, with a high degree of integration and interdependence between systems as well as a large degree of uncertainty. Modelling and Simulation (M&S) based OR forms a critical component of many evidence-based decision making processes within Defence, allowing decision makers the opportunity to explore scenarios that are too complex or too costly to test, and on problems where real-word validation and feedback on the results is unlikely outside of wartime, and could have major consequences if wrong. As the decisions being made based upon the models need to be "contestable", so do the models and simulation tools.

In order for the M&S community to better support Defence's broad requirements, a community of practice has been established to bring together the practitioner community performing a component of this analysis, primarily focused on "hard-kill" engagements. While the focus is on practitioners of hard-kill analysis, the community could also discuss related activities such as hard-kill / soft-kill integration, or input into strategic level M&S. This Australian M&S-based Engagement Performance Analysis Community has helped lead the establishment of this MODSIM session, so in order to kick off the program this short presentation will provide an overview of the community, while also setting the scene for the session (which goes beyond just "hard-kill" engagement analysis).

The purpose of the Australian M&S-based Engagement Performance Analysis Community includes:

- Increase awareness of the role of M&S in decision making
- Increase awareness across Defence about our capabilities
- Facilitate collaboration
- Share / improve best practice
- Facilitate peer review
- Share data (where appropriate)
- Help clients identify appropriate skillset and activities
- Avoid duplication of effort

The Australian M&S-based Engagement Performance Analysis Community consists of a range of members from across DSTG, broader Defence and industry. The boundary of the community is reasonably fluid, but the broad focus is on M&S based "hard-kill" analysis at the engagement-mission level. So if you are a member of the Defence community who performs engagement or mission level "hard-kill" analysis and want to engage with your peers, or, if you are a Defence client and leverage (or would like to) M&S based-analysis to support your decision making, please come join us for this presentation and this session.

Keywords: *Modelling, simulation, combat, engagement*

Hierarchy of evidence: A methodology for interpreting and summarising the predicted performance of weapons

W. Power [a], T. Goss [a], N. Tomecko [a], E. Dawson [a], and S. Rajesh [a]

[a] *Defence Science and Technology Group, Edinburgh, South Australia*
Email: wayne.power@dst.defence.gov.au

Abstract: The Australian Department of Defence is budgeted to spend over $86B AUD on Capability Acquisitions over the next five years (Commonwealth of Australia, 2021). In order to appropriately spend this funding and have the necessary strategic impact on the security of the nation's future, senior decision makers require the best possible evidence when making force design and acquisition decisions. However, the availability of such evidence is sometimes sparse due to a range of reasons. These reasons can include the cost of testing expensive military systems in combat like scenarios, the fact that some systems do not yet exist, and restrictions on the release of data when it does exist.

In order to support capability decision making, the Australian Defence Science and Technology Group (DSTG), uses a range of different techniques to predict the likely effectiveness of military systems in future engagement scenarios. However, given the sparsity and diverse nature of technical and performance data, from live trials to design requirements of future systems, multiple, and possibly conflicting, evidence data points could exist. Each of these pieces of evidence need to be considered and weighted in the context of the strength of evidence held by each data point when making decisions, as the consequence of not making the correct decision can be catastrophic.

The Weapons and Combat Systems Division (WCSD) of DSTG, employs detailed modelling and simulation to help contribute to the generation of such evidence. In order to help decision makers understand and interpret different types of evidence when making strategic decisions, this presentation will described a proposed methodology for interpreting and summarising the likely effectiveness of weapons and combat systems (although this methodology may be more broadly applicable).

The hierarchy of medical evidence is used to classify different types of evidence by quality, from anecdotal case series at the bottom, through to systematic reviews and meta analyses at the top, in order to help set the standard of care for physicians (Burns, et al., 2012) (Murad, et al., 2016). Inspired by this hierarchy of evidence, WCSD has developed an informal hierarchy of evidence for weapon effectiveness, as well as an associated methodology to help guide analysts and decision makers through the process of interpreting a range of different types of data on the same weapon or combat system.

This presentation will describe this hierarchy of evidence and methodology for interpreting and summarising the likely effectiveness of weapons and combat systems, its potential application, as well as its limitations.

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Keywords: *Defence, engagement analysis, hierarchy of evidence, evidence-based decision making*

An instance space analysis of combat simulations to understand the impact of force and information advantage on survival ratios

K. Smith-Miles [a], **S. Bista** [b] **and L. Jiang** [b]

[a] *School of Mathematics and Statistics, University of Melbourne,* [b] *Defence Science and Technology Group, Department of Defence, Canberra*
Email: smith-miles@unimelb.edu.au

Abstract: Instance Space Analysis (ISA) is a new methodology to rigorously "stress-test" algorithms to gain visual insights into their strengths and weaknesses. A diverse and comprehensive set of test instances is used to construct a 2D visualisation of the entire space of possible test instances, within which the performance of algorithms and the sufficiency of the available test instances can be scrutinised. In particular, test instances can be scrutinised for their diversity, unbiasedness, discrimination power, and real-world-likeness. Regions in the instance space where an algorithm has statistical evidence of good performance are generalised to form an algorithm "footprint", where machine learning methods are used to predict expected good performance on untested instances. The properties of algorithm footprints, including their area, density and purity, provide objective measures of comparative algorithm performance, rather than the traditional approach of on-average reporting of a performance metric over a test suite. ISA essentially unlocks the test suite to expose algorithm strengths and weaknesses, explaining how test instance characteristics affect algorithm performance.

The aim of this study is to explore for the first time how ISA can provide insights into combat simulations to understand the impact of defence force design on combat outcomes. Specifically, the study has focused on exploring how force advantage and information advantage, in the form of additional joint force assets and extended technological capabilities, can affect improved survival ratios of force assets at the end of the combat. Employing ISA to explore such questions has required a novel reinterpretation of the terms "algorithm" and "test instance" in order to map the ISA methodology onto the combat context. The study analyses data based on simulation runs from the JFOrCE agent simulation tool (Au et al., 2018), which simulates a fictitious combat between blue and red teams. Two data sets have been generated using the JFOrCE simulation comprising: i) 1854 force scenarios where the red and blue teams have identical initial assets with varying technological capabilities; and ii) 57 force scenarios where the red and blue teams have varying initial force assets with identical technological capabilities. An instance space is created using these datasets where "algorithm" success is defined as the Blue team (Experimental Force) having a better survival ratio of all assets compared to the Red team (Opposing Force). Analysis of the instance space reveals how the simulation parameters that define red and blue force attributes determine the outcomes of a simulated battle, with particular focus on those attributes that represent a significant force size or information advantage through technological capability.

The results show that identical initial force data is unbiased and quite comprehensive, with clear indications of how key force capability attributes determine the probability of success. It is clear from the visualisations obtained that loss is inevitable if the opposing force has an advantage in the form of superior jet sensor range, when loss is defined as poorer survival ratio of assets. Likewise, a win is guaranteed if the team has a superior jet sensor range. There are other more nuanced conditions involving combinations of force attributes, that make probability of win or loss high. These include likely wins if submarine sensor ranges are higher, and if shared communications offer an information advantage. Exploring the varied initial force scenarios, the study was also able to confirm that an advantage in the number of jets can overcome disadvantage in terms of jet capabilities. These findings roughly support those of previous studies with related but different simulation datasets (Au et al., 2018). Since the datasets are fictitious, these conclusions are inconsequential. However, the aim of this paper is to demonstrate the utility of the ISA methodology, by reassuring visualisations of these sensible relationships, and to show the potential for greater insights with additional simulation data. Scrutinising the diversity of the entire instance space, we show that there are simulation scenarios that could be explored where the combat outcomes are currently less predictable. There is also an opportunity to explore simulation outcomes for other parameters that define combat rules and strategies.

Keywords: *Instance space analysis, combat simulation, information advantage, force advantage*

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The STELaRLab model for modern, rapid & adaptive operations analysis

S. Thompson [1], **A. Dasgupta** [1], **S. Beinke** [1], **D. Tissa** [1], **M. Turner** [1] **& K. McDonald** [1]

[1]*Science Technology Engineering Leadership and Research Laboratory (STELaRLab), Lockheed Martin Australia, Melbourne 3000, Australia*

Email: samuel.thompson@lmco.com

Abstract: Modern, Adaptive, Rapid Operations Analysis at STELaRLab is built upon a suite of customizable and powerful Modelling and Simulation (M&S) tools that are harnessed by analysts with extensive subject matter expertise. By utilising a flexible, modular methodology that incorporates GUIDEx principles of valid experimental design and engineering rigour, different M&S tools can be quickly adapted to study future complex military engagements while managing often competing constraints on fidelity and time.

This adaptability is enabled by employing a variety of simulation tools across a spectrum of fidelity levels. At one end, "gamification" approaches and/or commercial tools using effects-based modelling are employed to test algorithmic behaviours under controlled conditions or to broadly replicate complex processes. At the other, high-fidelity simulation environments replicate the physics more faithfully by solving the governing equations at play, and can be employed to verify the assumptions and outputs of lower fidelity codes at key data points. As these high-fidelity environments are resource-intensive, effects-based tools are frequently paired with simple analytical approaches to provide rapidly verified results. This methodology was used during a recent study of future collaborative systems, using both an analytical Excel-based technique together with simulations in COMMAND PE. The Excel-based analytical tool was adopted to provide a rapid initial understanding of possible collaborative system deployments, with select scenarios then run in COMMAND PE. The ability to run customised scripts is used to extend default COMMAND PE behaviour and represent conceptual systems that respond to an evolving environment. Future work will incorporate additional results and models generated from higher-fidelity proprietary simulation tools to allow more detailed analysis and generate further insight.

Fundamental to this multi-layered, multi-fidelity approach is the ability to tailor the M&S approach to different project requirements. At one level, the use of common commercial effects-based tools permits rapid turn-around times and facilitates result releasability to a broad audience. At another, selective introduction of sensitive datasets or proprietary high-fidelity models allows a granular trade-off of these characteristics against increased operational relevance or physics-based realism. This modular approach permits the M&S framework to be customised to align with study objectives and supports the inclusion and early risk-reduction of state-of-the-art methodologies during study execution to avoid impacting project delivery outcomes.

A key challenge is access to high-quality data sets, especially for M&S activities conducted by industry in the public domain that centre on current or future systems. This extends to both Allied and adversary system data, as well as information about operational tactics and deployments. In order to minimise a reliance on sensitive data, unclassified system data and engineering assessments are adopted in the first instance. Where gaps remain in available system information, stochastic approaches such as Monte-Carlo analysis are employed to assess the sensitivity of study outcomes to assumptions about system performance or behaviours. This sensitivity analysis can be used to overcome uncertainties in system data and also provides greater insight into the parameters that drive vehicle subsystem performance. Other challenges in assessing model fitness-for-purpose, and in comparing Measures of Effectiveness (MoE) between different analysis cases, are more nuanced but have been mitigated through the deployment of multi-disciplinary project teams that draw on their combined expertise to evaluate the consequences of underlying model/MoE assumptions on the analysis.

The efficacy of a modular and adaptive Operations Analysis approach has been successfully demonstrated in recent studies exploring conceptual force design requirements. The framework forms the foundation of STELaRLab's Operational Analysis activities and will continue to evolve as new state-of-the-art toolsets and methodologies are incorporated as part of a mature M&S capability.

Keywords: *STELaRLab, operations analysis, modelling, simulation*

Causality modelling of simulated temporally indexed events to construct a combat narrative

J.K.R. Tiong [a] and **B.A. Chiera** [a]

[a] *UniSA STEM, University of South Australia, Adelaide, South Australia, 5000*
Email: junia.tiong@unisa.edu.au

Abstract: Combat simulation studies are commonly used to support decision-making on the basis of competing outputs, simulated under comparable conditions, for a selection of input design points. Such simulators have long been in use to support analysis in force design, operational requirements, mission area analysis and force-on-force analysis, necessitating high-resolution, closed-form and stochastic simulation capabilities. Each simulation typically runs as a black-box, making it difficult to discern the intermediate stochastically-varying series of events that form part of the combat narrative, detailing the sequence of events that led from the simulator inputs to the observed outputs.

Although the simulator runs in black-box mode, internal simulator data on stochastically-varying temporally indexed events over the combat spatial region are also captured. These events record an ordered series of events that, although stochastically seeded, reflect the fundamental logic of cause and effect. Understanding these event series through appropriate statistical modelling has the potential to provide key insights into the combat mission narrative and support decision-making around combat missions.

In this paper we present a first step towards constructing a combat mission narrative to support decision-making via a case study of internal combat simulation event series and their associated outputs. Statistical modelling of the internal data is challenged by the underlying simulator mechanisms – the use of Common Random Numbers (CRN) to reduce the variability in simulation output. CRN simulators are fraught with difficulties as they violate key statistical assumptions by design, requiring alternative, robust methods of analysis.

We adopt the use of the statistically robust Event Coincidence Analysis (ECA) to capture causality between events by providing a framework for quantifying the strength, directionality and time lag between two event series. The use of ECA is novel in this area of application; ECA has been recently adopted in the literature, predominantly in the areas of ecology, environment and health and is relatively under-explored in Defence, with current areas of application including armed conflict and hate-speech triggered terrorism.

An attractive feature of ECA is that it allows for significance testing of causality between two series, based on stochastic point processes with a prescribed inter-event time distribution and other higher-order properties, thus providing a differentiation between coincidence and causal events. Specifically, ECA considers two types of causal behaviour - *precursor* and *trigger* - with the former describing a series of events that typically occur before a secondary event takes place (mediated cause-and-effect) whereas the latter captures the concept of direct cause-and-effect between two events. Extensions of ECA include aggregation and conditionalisation; the former providing an integrated measure for coincidences that occur between several pairs of event series subject to some meaningful grouping mechanism and the latter allowing for the flexibility of interlinking multiple causal event series, to allow for conditioning of events on specific situations.

The R library *coincalc* was used to implement ECA as part of constructing a combat narrative. The case study provided four event series of interest - *Movement, Detections, Shots* and *Kills* – yielding combat narratives around the progression of Movement leading to Detection, being Shot and a Kill. Suggested combat narratives arising from the analyses conducted herein were: (i) standing can act as either a precursor or trigger to being identified or recognised while detection is a mediating, not direct, trigger for being shot. These results were supported by two different ECA methodologies; and (ii) for those simulations resulting in combat mission failure, precursory behaviour led to the failure of the overall mission over a relatively short time window, rather than a single, or series of, direct triggers.

Keywords: *Combat simulation, temporally indexed event series, event coincidence analysis, precursor and trigger behaviours, combat narrative, decision-making*

A queueing theoretic approach for performance prediction of collaborative active protection systems

Graham V. Weinberg [a]

[a]*Defence Science and Technology Group, Joint and Operations Analysis Division, Edinburgh, South Australia, 5111, Australia*
Email: Graham.Weinberg@dst.defence.gov.au

Abstract: The defence of a team of armoured fighting vehicles (AFVs) against both military and improvised threats is of considerable importance to defence agencies. Active protection systems (APS) equip a vehicle with both automatic threat detection as well as countermeasures. A concept of significant contemporary interest is that of collaboration between vehicles equipped with APS. In this context, collaboration permits information on threat detection and tracking to be shared amongst members of the combat team. This then allows threat countermeasures to be both scheduled and then activated.

A series of studies conducted by Defence Science and Technology Group (DSTG) have generated a number of stochastic models to examine this concept. In the first instance a discretised time model was produced, which then allowed performance prediction of collaborative APS (C-APS) to be undertaken. A limitation of this approach is that threats may arrive at any point between discrete time epochs, and hence the discretised model does not reflect observable reality. Hence a second analysis investigated the application of jump stochastic processes to undertake performance prediction in continuous time. This approach provided quantitative performance prediction when the AFV is subjected to up to two threats. When the number of threats exceeds two the analytic solution increases in complexity and becomes difficult to utilise, justifying the search for an alternative performance prediction methodology.

In order to produce a manageable framework to conduct C-APS performance prediction in the presence of more than two threats, a queueing theoretic approach has been formulated. This scheme views the vehicles with effectors as a network of queues, where a threat is interpreted as a customer arriving into a particular queue. The process of elimination of the threat is the customer's service time in the respective queue. This formulation of the C-APS performance prediction problem then yields a useful expression for the probability that threats are neutralised by a given time. Consequently this provides a mechanism to assess the performance of various configurations of C-APS.

Due to the fact that directed energy weapons (DEWs) are of contemporary interest for threat defeat with AFVs, the specific model performance prediction examples will utilise C-APS when the countermeasure is provided by high energy laser (HEL) DEWs.

Keywords: *Queueing models, armoured fighting vehicles, active protection systems, collaborative defence, performance prediction*

Determining Performance Limits for Directed Energy Weapons in Collaborative Active Protections Systems

Graham V. Weinberg [a]

[a]*Defence Science and Technology Group, Joint and Operations Analysis Division, Edinburgh, South Australia, 5111, Australia*
Email: Graham.Weinberg@dst.defence.gov.au

Abstract: The application of directed energy effectors, and in particular high energy lasers, is of considerable importance for the future land fighting force. Such weapons have the utility for long distance precision strikes against targets, and so merit investigation for potential application in future emerging technology. Collaborative active protection systems is an emerging capability which is designed to provide automatic threat defence for an armoured fighting vehicle team. Performance prediction analysis of such future systems is thus of considerable importance to defence stakeholders.

Recent studies have shown that the performance analysis of such systems can be very complicated, although in some cases this complexity can be reduced. The latter is certainly the situation when the number of threats the combat team is facing is smaller than the number of available countermeasures.

Hence this paper proposes a methodology where this restriction can be eliminated. The key to this is to focus on the likelihood of at least one threat being eliminated, and examining performance prediction curves to assess this likelihood. Once consequence of this is that it becomes necessary to introduce a "rule of thumb" to interpret these performance prediction curves relative to the threat. To illustrate the potential of the methodology, an illustrative example will be analysed. This hypothetical example assumes some generic properties of a high energy laser directed energy weapons, operating in a collaborative active protection system context. It will be shown for this example that threats travelling at speeds significantly smaller than Mach 1 are likely to be countered through the collaborative active protection system, while the rule of thumb establishes that threats exceeding this speed are unlikely to be defeated.

Keywords: *Armoured fighting vehicles, active protection systems, directed energy weapons, performance limits*

INVITED PAPER

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Analytic wargaming to inform Australian Defence Force design

GPCAPT Philip Arms

Department of Defence, Canberra, Australian Capital Territory
Email: Philip.arms@defence.gov.au

Abstract: The Australian Defence Force (ADF) has recently concluded a major experimentation campaign over the past 18 months to provide advice to current acquisition projects and inform the design of the future force. A major outcome of this work was the design of coherent, achievable and targeted workforce growth options. This program was framed by the Force Structure Plan 2020, leading to a modified investment program committing over $270 Billion over the next decade, and informing areas for further concept exploration and capability development.

The Joint Experimentation Directorate (JED) is the lead agency within the ADF's Force Design Division (FDD) for joint experimentation. Joint Experimentation directly supports decision making for force design and joint capability development. This Directorate provides decision support through the provision of experimentation for concept exploration, force design and risk qualification, employing novel approaches to wargaming within analytical programs.

This invited paper by GPCAPT Philip Arms, Director of Joint Experimentation in Force Design Division, Australian Defence Headquarters will cover the role of experimentation in force design, methods used, identified components of a military experiment, and a discussion on the techniques commonly used by JED in the execution of experimentation and wargaming.

Keywords: *Force design, capability development, decision making, wargames*

Consideration of enabling and enterprise functions within Defence force design

J. Boyce [a], **N. Tay** [a], **C. Rowe** [a]

[a] *Defence Science and Technology Group, Canberra, Australian Capital Territory*
Email: jake.boyce@dst.defence.gov.au

Abstract: Defence force design is the process for planning and designing the future Australian Defence Force (ADF) and its supporting organisation. Traditionally, force design has focussed on major equipment acquisitions such as ships or aircraft, not least because of the long lead time for delivery of such assets. However, there is a need for a coherent force design process that provides better long term planning for the enabling and supporting functions, in addition to the warfighting functions. This paper describes the novel application of a prioritisation method to assess investment options relating to supporting, enabling and business functions of Defence, which are collectively described as enterprise functions. These enterprise functions include, for example, capability acquisition, facility management, finance, military strategy, force design, science and technology, and the engagement functions with the rest of the Australian Government.

The Australian Department of Defence operates a biannual cycle called the Defence Capability Assessment Program (DCAP), which is the analytical process that assesses strategic guidance and determines organisational design and investment priorities to achieve the Defence strategy. The various stages of the DCAP include collating gaps and opportunities, prioritising needs and developing force options, then assessing and prioritising these options. Selected options are included in the Integrated Investment Program (IIP) in order to maximise the overall benefit to Defence for a given budget across the next 20 years. DCAP has historically focussed on major equipment acquisitions, but the 2020 Force Structure Plan stated that Defence would return to government with a detailed proposal for workforce growth, which was then addressed within the DCAP 2020-21. This was the first DCAP with a primary focus on workforce.

The DCAP is based on a Capability Based Planning (CBP) approach, which is best suited to assess the operational components of Defence that contribute directly to a warfighting scenario. However, it is conceptually difficult to apply the same approach to the enterprise force options. For example, is it possible to estimate the contribution of a pay clerk to the ADF defeating an adversary in battle? DCAP 2020-21 investigated innovative ways to assess 'enterprise' force options to improve these functions in parallel with the 'operational' force options, which were assessed through a CBP approach.

The Best Worst Method was selected as the most robust, suitable prioritisation tool to assess the enterprise options. Representatives from every Group and Service of Defence were asked to generate a narrative of how each of their proposed force options mitigates risk to Defence objectives, including the targets set out in the Defence Corporate Plan. Each Group and Service then used these narratives to select their most-valuable (best) and least-valuable (worst) force options and to make a relative comparison of every other option against these best and worst. These pairwise comparisons were converted to a quantitative value score for each option. The individual lists were displayed in a visual 'stitching' tool that allowed linear scaling and translation of each list to adjust their position on a common scale. Facilitated discussion amongst the representatives generated an agreed list of the relative values of every option. These enterprise option scores were then stitched together with the operational scores for input to a portfolio optimisation tool and generate proposed portfolios of investment.

This process demonstrated one approach to the treatment of supporting and enabling functions that complements the assessment of warfighting capabilities. When presented to senior decision makers, the enterprise scores were accepted as a fair representation of the relative value of the proposed options. The output of DCAP 2020-21 will underpin both the updated IIP and the Defence workforce growth options developed in response to the 2020 Force Structure Plan.

Keywords: *Force design, capability development, decision making, organisational design*

Project portfolio optimisation and scheduling using temporal tolerances

G. Calbert [a]

[a]*Defence Science and Technology Group, Edinburgh, Adelaide, South Australia, 5111*
Email: Greg.Calbert@dst.defence.gov.au

Abstract: In financial portfolio optimisation, there is a hitherto agreed definition of the value of a particular series of investments, this being financial returns. When one considers applying the machinery of portfolio optimisation in Defence, the objective is to select and schedule a subgroup of projects. Such projects are drawn from a larger pool, typically extant and new projects. There is no fiscal "return," as projects are public goods. Each project must be assigned a value depending on its potential start time. Ideally each project has two attributes, a vector of starting-time dependent values and a vector of costs which commence from the project starting time. The optimised portfolio ensemble must meet time-dependent budget constraints.

The optimisation formalism is that of a multiple knapsack problem and the methods of integer programming apply. In practice forming starting-time project values is contentious. Unlike financial portfolio theory, there is no agreed approach to value determination, as there is no analogy to currency. It is this issue that drives the approach developed here. The starting-time values for projects are elicited through a specific pre-defined time-dependent functional form of value. The parameters of this functional form are then derived by asking *what is the ideal project starting-time and how tolerant is the subject matter expert of that time?* By doing this, one introduces an agreed currency for projects, deviance from this ideal time. This pre-defined functional form of the starting-time values, is called in this paper a temporal tolerance function.

In this paper the multi-knapsack problem is explored with temporal tolerance starting-time value functions. In Section 1 the issue of determining the value of the public good's military capability is discussed. In Section 2 then describe the multiple-knapsack problem and introduce a number of temporal tolerance functions. In Section 3 computational experiments are conducted with such functions to determine portfolio structure properties, such as optimised value and time deviance as tolerance levels change. Finally in Section 4 the paper is summarised and the general problem understanding the statistics of project selection, as a function of cost structure and value function structure is discussed.

Keywords: *Portfolio, optimisation, public goods, value*

Crowdsourcing scenario linchpin variables

Richard de Rozario[a] and **Niem Tri**[b]

[a] *The Hunt Laboratory for Intelligence Research, University of Melbourne, Parkville 3010, Australia,*
[b] *Defence Science and Technology Group*
Email: richard.derozario@unimelb.edu.au

Abstract: In partnership with the Defence Science and Technology Group (DSTG), The Hunt Laboratory for Intelligence Research at the University of Melbourne conducted research through a series of online 'crowdsourced' exercises to investigate linchpin variables in future conflict scenarios. Linchpin variables are key events, processes, and sociopolitical, economic or technical factors that are necessary for the scenario to eventuate. These key variables frame the future scenario space and can be used for subsequent modelling.

Our methodology builds on previous research (de Rozario, 2015) to elicit key operational factors in extreme risk scenarios such as major cybercrimes and natural disasters. The approach works backwards from scenario end-situations and asks participants to identify linchpin variables and explain plausible pathways from the current situation (today) to the scenario end. A second stream of research (van Gelder et al., 2020) was the development of a platform for crowdsourcing complex analysis. Our methodology, called "Contending Analyses" (CA), improved the quality of analysis by increasing the cognitive diversity that was applied to the analysis. This included improving the effectiveness of each participant's contribution and consideration of diverse ideas to address a complex problem. The platform also enabled the consolidation, selection and development of a single coherent team answer. The method relied on developing collaborative software features to support cognitive devices such as anonymity, flexibility of contribution types, simultaneous communication of different kinds (e.g. contribution, coordination, mutual support) and the evaluation of ideas.

Since 2018, the University of Melbourne has run several experiments demonstrating the potential of the CA approach in producing high quality analysis, using teams of participants from the general public and from Australian organisations. In 2020, DSTG sponsored the University to run such an experiment, with a focus on eliciting linchpin variables in scenarios relevant to Defence. The University again invited public teams and DSTG also announced the exercise within the Department of Defence to encourage voluntary participation by Defence personnel.

Five teams, each of about 40 participants, worked anonymously on a web-based platform on four diverse and hypothetical scenarios of future conflict situations that involved an Australian whole-of-government response: a harbour port occupation scenario; a UN peace keeping campaign; a coronal mass ejection event; and a hacking event of autonomous freight and transportation systems. Three of the teams were composed of general public participants and two were recruited from Australian Government organisations.

The teams produced plausible and diverse pathways, with in-depth narrative explanations, and with enough suitable content to identify the desired linchpin variables. However, more detailed analysis would be required to identify the linchpin variables in sufficient detail for subsequent modelling or for use as intelligence indicators. Moreover, the methodology seems to work better with public teams than with organisational teams, which suggests that further research is needed to adapt the methodology to organisational contexts.

Some further research has already commenced to adapt and improve the methodology for analysis with organisational teams and in an organisational context. In particular, we are currently investigating a mixed elicitation method, where some activities are in the form of joint, real-time sessions and some are asynchronous platform based. Further work is also conducted on adapting the methodology to more generic collaboration platforms, such as Confluence (developed by the Atlassian software company).

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Keywords: *Scenarios, crowdsourcing, key variables, qualitative modeling, elicitation*

Exploring possible conformity effects in military experimentation: A pilot study

Lauren Francis[a]

[a] *Defence Science and Technology Group*
Email: lauren.francis@dst.defence.gov.au

Abstract: The Australian Department of Defence uses knowledge elicitation methods to gather information from subject matter experts (SMEs) to aid decision making. The information gathered needs to be as accurate as possible because large scale decisions, such as acquisitions and future defence force plans, are informed by it. The group feedback aspects of these knowledge elicitation methods may cause a conformity effect that creates a false consensus and obscures the true variability in the SME responses.

Conformity is the social influence phenomenon where individuals change their opinion or behavior to comply with the majority in the group (Rosander & Eriksson, 2012; Wijenayake et al., 2020). This conformity behavior is thought to be driven by a desire to be accepted by the group and can lead to individuals not expressing their opinions in group settings (Wijenayake et al., 2020). This obstruction to individuals sharing diverse independent responses due to conformity contradicts the aims and requirements of knowledge elicitation (Burgman, 2016). There are some methodological aspects of knowledge elicitation that may induce conformity in SMEs.

Several knowledge elicitation methods, such as the IDEA (Investigate, Discuss, Estimate, Aggregate) and Delphi protocols, use a group feedback process where after each individual has given their answer to a question, they are shown a bar chart of the group responses and then given the opportunity to reassess their answer (Burgman, 2016). This feedback step may cause a conformity effect where each individual moves their answer towards the majority group answer seen in the bar chart in order to conform to the majority in the group. Previous research into conformity has found some evidence of conformity occurring in these feedback conditions when using categorical questions (i.e. each participant choosing one of the options presented) (Wijenayake et al., 2020). Other kinds of question and answer types, such as predictions and numerical responses, have yet to be explored in the literature.

The current research aims to expand upon the previous research and investigate whether a conformity effect occurs in complex prediction questions requiring continuous numerical responses. In the proposed method, participants will be given a link to an online survey where they will be randomly allocated to one of two conditions which vary the order of the questions and the type of feedback given. They will be asked a series of short-term future prediction questions, such as predicting the number of international arrivals in Australia within a month. For each question, the participants will be asked to make their prediction, and then shown a fabricated bar chart that shows either a clear majority or no clear majority and given the opportunity to change their answer. The results could then be statistically analysed to test for conformity occurring, such that participants shown the majority bar chart feedback are more likely to change their answer towards the majority answer than the participants shown the no majority bar chart feedback.

A pilot study has been conducted to test the method and processes with a small sample size. The results of the pilot study are to be presented to support verification of the method and analysis in testing for conformity effects. It is intended that future experiments be conducted with sufficient participant numbers to support a statistically significant comparison of the conformity effect.

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Keywords: *Conformity, knowledge elicitation, social influence, group processes, military experimentation*

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Adversarial Concept Exploration: Blending Adversarial Scenario Analysis and Concept Exploration

T. Goss [a], **P. Nguyen** [a], **M. Tong** [a] **and S. Rajesh** [a]

[a] *Defence Science and Technology Group, Edinburgh, South Australia*
Email: Tristan.Goss@dst.defence.gov.au

Abstract: The Defence operating environment faces a high degree of change due to new technologies, opportunities and challenges (Department of Defence, 2020). Defence forces that are agile and able to exploit new technologies and opportunities will likely have significant advantage as situations evolve. Success will also require correctly identifying which opportunities have the highest military utility, i.e. which opportunities will be the most useful to Defence. Questions of this nature can be addressed through concept exploration activities in order to support evidence-based decision-making for technology and capability investment.

Identifying promising emerging and new technologies then understanding their military utility can be difficult to achieve using numerical ('hard') operations analysis (OA) methodologies. In general we want explore options as early as possible, which means there are still many unknowns about system performance and applications. If we were to try to apply numerical solutions to the problem, the uncertainty would not lead to conclusive results. Similarly, from a military utility perspective it can be difficult to envisage how to use a concept that has yet to be developed. This can often lead to an impasse in exploration discussions as in the example dialogue:

Force Designer: I'd like to understand how your technology could be useful. What can it do?
Technologist: It's complicated. That depends on how you want to use it.
Force Designer: I can't tell you how I want to use it without knowing what it can do!

A possible approach to this challenge is the Adversarial Scenario Analysis (ASA) methodology, an iterative approach to exploring military utility. ASA incorporates both subject matter expert judgement ('soft OA') and hard OA methods to assess and improve the effectiveness of options (Pincombe et al. 2005, Pincombe & Pincombe 2010). Over each evolution the scenario and response options are modified to test the robustness of possible solutions. As the solutions evolve performance is compared against quantitative and qualitative measures with the goal of producing better solutions that ideally converge to one or more optimal solutions.

As above, early-stage concept exploration activities may include too much uncertainty around technology performance and military utility metrics to effectively apply hard OA assessment. Therefore a new process focused exclusively on soft OA methods was adapted from ASA: Adversarial Concept Exploration (ACE). ACE cannot identify optimal solutions as it lacks a hard OA component, but has proven effective at highlighting key performance questions which is a critical objective for concept exploration. The iterative nature of the method successfully addressed the common impasse described above using only soft OA techniques. As the concepts mature it is likely that the outputs of ACE could be used as seeds for a future ASA process.

This presentation will outline the ACE process as well as demonstrate a fictitious worked example.

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Keywords: *Defence, concept exploration, evidence-based decision making, military utility, operations analysis*

A layered meta-data approach to the design of joint experimentation data warehouse

Li Jiang, Maria Boyle, Kevin Johns, Chitra Muniyappagounder Subramanian and Sanat Bista

Strategy and Joint Force, Joint and Operation Analysis Division, (JOAD) Defence Science and TechnologyGroup, Department of Defence
Email: li.jiang@dst.defence.gov.au

Abstract: Force design activities such as Force Structure Planning (FSP), wargaming and experimentation generate large amounts of data in different formats. Current in-house data management systems are limited in their ability to store and manage data efficiently. The development of a Joint Analytics and Reporting System (JARS) as a data warehouse for experimentation activities will provide the necessary infrastructure to support data storage, management and retrieval. Availability of quality, fit-for-purpose data via JARS will also enable the use of advanced analytics techniques to support evidence-based decision-making. Using historical experimentation data to support the planning of future activities is challenging as data sources, formats and data quality are often variable. In this paper, we propose JARS as a practical solution and present a layered metadata model approach based on our research and analysis of the historical data. As part of this endeavour, we conducted *requirements discovery* workshops to assist in the design of JARS. The JARS schema was developed based on database theory, metadata design principles, and best industry practices such as the FAIR principles (Findability, Accessibility, Interoperability, and Reusability of digital assets). Furthermore, we considered the trade-offs between the principles of database design, data integrity, data processing complexity, and completeness and efficiency of querying. The metadata model contains three-layers of information: Campaign layer, Activity layer, and Extensible layer. The Campaign layer contains Campaign name, Campaign objectives, and so forth. The Activity Layer contains metadata information such as Name, Status, Location and Scenario used. The Extensible Layer contains more information and data required for finding nuanced information. This layered structure provides a flexible and effective way to store and query various metadata information as required. It can also assist in achieving a balance between information integrity and data complexity, and between completeness of information and efficiency of data retrieval. The latter is often a challenge in database design. This paper aims to present theresults of our past research and ongoing work. The significance of JARS and the future work are also discussed.

Keywords: *Metadata, data warehouse, force design, design principle, decision support system, experimentation*

A regret-based incremental elicitation for multi-criteria force design

V. Mak-Hau [a], T. Cao [b], J. Yearwood [a]

[a]School of Information Technology, Deakin University, Waurn Ponds, Vic 3216, Australia
[b]Joint and Operations Analysis Division, Defence Science and Technology Group, Australia
Email: vicky.mak@deakin.edu.au

Abstract: We aim to develop a framework for defence force design multi-objective decision-making problems where there are multiple decision makers each with a potentially different set of priorities, but only one solution is required in the end in practice.

Benabbou et al. proposed an interactive preference elicitation approach designed for problems with a single decision maker in the Proceedings of the AAAI Conference (2020). In this approach, a linear scalarizing function is used for the multiple objectives. In each iteration, a population of different scalarizing parameter vectors are generated and the associated single-objective optimization problems are solved one by one, each providing a different "optimal" solution. Following that, the search space of the scalarizing parameters is reduced through preference elicitation of pairwise "optimal" solutions obtained from the parameter vector population as each preference produces a cut to the feasible parameter set. The stopping criteria is controlled by the calculation of a regret value. If, in any iteration, out of all solutions found, there is a solution that returns the smallest maximum pairwise regret value and that the value is smaller than a predetermined tolerance, then the solution will be chosen as the final optimal solution.

In this paper, we propose a number of adjustments and modifications to the Benabbou et al. approach required for our intended application - Defence Force Design. We provide an insight on the impact of having multiple decision makers instead of just a single decision maker. It may seem counter-intuitive, but with multiple decision makers, we expect that the search space of the linear scalarizing function parameters converges to a single point much quicker if the decision makers conflict with each other in their preferences. We also propose a hierarchical approach to deal with high dimensional objective space as well as alternative scalarizing function parameter search schemes.

Keywords: *Multi-objective optimization, Regret model, preference elicitation, multiple decision makers*

An evaluation model and tool for Defence capability options

M.-T. Nguyen[a], A. Coutts[a], J. Knoll[a], M. Zuparic[a], J. Peacock[a], D. Bilusich[a], M. Galister[a] & K. Johns[a]

[a]*Joint & Operations Analysis Division, Defence Science and Technology Group, Australia*

Email: {Minh-Tuan.Nguyen|Andrew.Coutts|Julia.Knoll|Mathew.Zuparic}@dst.defence.gov.au

Abstract: The 2020 Force Structure Plan (FSP) sets out adjustments to Defence capability investments and will provide options to deliver the new strategic objectives outlined in the 2020 Defence Strategic Update[1]. This plan is developed and reviewed within a four year Defence Capability Assessment Program (DCAP) cycle. The first two years of the cycle delivers an update to Defence on force structure in response to changes in strategic circumstances and policy, while the full cycle delivers a revised FSP. Defence Science & Technology Group (DSTG) have proposed an evaluation approach by integrating various methodologies: Bayesian network (BN), multi-criteria decision making (MCDM), Monte-Carlo simulation with parallel computing and multi-objective evolutionary algorithms (MOEA). By working with Force Design Division (FDD) (within the Vice Chief of the Defence Force (VCDF) Executive), who are responsible for delivering the FSP, we have developed a Bayesian Reasoning Value Model (BRVM) and a tool for managing and analysing data collected from subject matter experts (SMEs). An evaluation of Defence capability options is then conducted via this Bayesian Network Analysis Tool for Force Structure Plan (BNAT-FSP).

Interactions among the force structure components (Defence element, force package, operational effect and mission) are defined by logical or physical links which complicate the evaluation of the dependability of these force structure models. In addition, the different operational scenarios and threats present a challenge to decision makers (DMs) in providing a clear answer to the problem of determining the value of proposed capability options. BN is employed to establish a qualitative and quantitative representation of the relations between the variables of the model considered and calculate standard values of uncertain capabilities (e.g. mission success, operation/force effectiveness, e tc). MCDM is designed to combine the influence of multiple BN models built from different scenarios/missions. With our BRVM reaching the size of thousands of variables, exact inference in BNs is apparently infeasible. We apply a stochastic sampling method together with Monte-Carlo simulation, which is run on parallel virtual computers, for reaching evaluation results at our desired accuracy. MOEA is also used in our sensitivity analysis to find the optimal level of mission success and the impact level of each contributing force.

The proposed multi-method approach provides modelling and data collection structures that assist in making explicit the force structure, scenario parameters, and the DMs' preferences. This significantly reduced the time-consuming elicitation process, and helped us to deliver the option evaluation results on time at a desired accuracy.

[1] https://www1.defence.gov.au/strategy-policy/strategic-update-2020 (accessed 28 May 2021).

Keywords: *Bayesian network, BN, multi-criteria decision making, MCDM, analytic hierarchy process, AHP*

Building blocks for a holistic framework for Integrated Air and Missile Defence

S. Rajesh [a], N. Tomecko [a], E. Dawson [a] and W. Power [a]

[a] *Defence Science and Technology Group, Edinburgh, 5111, Australia*
Email: sreeja.rajesh@dst.defence.gov.au

Abstract: Integrated Air and Missile Defence (IAMD) is defined as the integration of offensive and defensive operations against air-breathing and missile threats, and is meant to counter an opponent's ability to degrade or disrupt operations and the projection of combat power (US Joint Chiefs of Staff 2013). For the purpose of this presentation, we have adopted this definition from the United States as it is a well-recognised, publically available definition of IAMD, and adapted it for the Australian context. Without being bound to a specific set of capabilities, the Australian Defence Force (ADF) can achieve the above in a variety of ways. For example, countering air and missile threats could be achieved by preventing the opponent from having the capability, so there are no such systems to launch. It could also be achieved by preventing them from launching their assets. While these constitute "left of (threat) launch" strategies, threat defeat could also be achieved by minimising their effects and preventing the opponent from achieving their objectives after launch. Given the variety of ways of countering air and missile threats, there are many ways an IAMD system could be designed. Decisions regarding where to invest to get the right balance of IAMD capability for the ADF so as to ensure dominance over current, emerging and future threats will need to be based on a good understanding of the various options discussed above, and how they can work together. Hence there is a need to develop a holistic framework to facilitate the exploration and assessment of various design paradigms for IAMD, which includes the integration of left of launch and right of launch options.

The initial focus of this work is to develop a conceptual framework by identifying and linking the different layers of an IAMD system to understand how they influence and impact each other. With this goal in mind, a workshop involving subject matter experts was conducted to collect data to start building a fully integrated IAMD framework. Conventional IAMD mainly comprises of active (such as intercepting with missiles and electronic attack) and passive defence (such as the use of cover, concealment, and camouflage, protective cover, and deception) measures. Command, control, communication, computers, and intelligence (C4I) is another crucial component of IAMD. These three, along with offensive strike operations that help to prevent the attack, form the "Four Pillars of IAMD" (US Joint Chiefs of Staff 1996, Kosar 2020). Since the four IAMD pillars capture both the left of launch and right of launch options, this formed the basis for our data capture.

The objective of the workshop was to understand the core components or "building blocks" that describe a holistic IAMD system and to identify how they are linked to each other. In order to achieve this aim, three activities were designed. The first activity helped to identify and capture the impacts and the consequent actions required to be performed by an effective IAMD system to disrupt the opponent at their different stages of attack. The second activity was conducted to capture example own-force capabilities (both current and future) that could perform these actions in order to identify tangible solutions to build upon. Finally, the third activity helped to draw and link the own-force capabilities in the sense, decide and act phases that can defeat the opponent. The outcomes of the workshop helped to capture an initial list of key IAMD capabilities and identified how they can be used to deliver impacts and disrupt the opponent across the four IAMD pillars. This presentation will discuss the framework that we have used to capture these results.

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Keywords: *IAMD, missile defence, active defence, passive defence*

Analytic approaches to understanding future Defence workforce needs

C. Rowe, A. Crockett, S. Rohan-Jones, S. Aljoofri, N. Tay, A. Coutts, C. Bishop, A. Pay, W. Sim, V. Date and J. Boyce

Department of Defence, Canberra, Australian Capital Territory
Email: cayt.rowe@dst.defence.gov.au

Abstract: A campaign of analysis has been conducted to help workforce planners to understand future Defence workforce requirements and design coherent, achievable and targeted workforce growth options for the Australian Defence Force (ADF). This paper reviews the wide range of analytical approaches that were employed to underpin the potential growth options, which will generate a robust, resilient and effective Defence workforce over the next 20 years.

In 2020, Australian Department of Defence released the Defence Strategic Update, accompanied by a new Force Structure Plan which detailed the government's intentions for capability investments. This 2020 Force Structure Plan identified that the Defence workforce needs to grow in order to support a larger number of more-complex capabilities, including to build capacity in cyber, intelligence, electronic warfare and space. An analysis campaign to review the long-term workforce requirements for Defence became the focus of the 2020-2021 Defence Capability Assessment Program, which is the primary force design process for the ADF. This analysis campaign brought together two distinct disciplines of capability-based planning and workforce planning. Capability-based planning focusses on maximising the "capability" of the force, being the ability to achieve an effect, and testing the effectiveness of these capabilities within the context of scenarios. However, understanding the strengths and limitations of workforce capability is much more challenging than the traditional assessment of weapon systems, and analysis methods from human resource management are also needed to ensure an achievable workforce plan.

Five complementary analytical approaches were employed, drawing on expertise in Defence People Group, Defence Science and Technology Group, and the Force Design Division of the ADF Headquarters. Based on a series of wargames, operational demand modelling provided a detailed estimation of the number and types of people Defence will need to meet a future warfighting scenario. A Bayesian network model captures how the constituent parts of Defence contribute in a warfighting context, and this model was used to quantify the expected benefit from proposed workforce investments. The supporting and enabling functions of Defence were considered through both a prioritisation of proposed investments and mapping how the entire organisation supports Defence capability.

Whereas the above methods focussed on future demand for workforce to deliver capability, supply modelling focussed on the ability to grow and train that workforce. The workforce growth model provides realistic estimations of achievable growth rates to inform both the likely limit on how quickly Defence can grow overall, and the ability to generate specific skill sets in different locations. It also provides guidance for how many recruits should be targeted to achieve the desired number of trained personnel, and this in turn informs the required investment in supporting functions such as facilities and recruitment.

The campaign of analysis to understand future Defence workforce requirements created new connections between different analysis methods. This strengthened each individual approach and enabled the design of coherent, achievable and targeted workforce growth options for Defence. The analytical campaign described in this paper has provided much-needed detail to underpin how Defence will reshape and reskill its workforce in response to emerging requirements.

Keywords: *Force design, capability development, decision making, personnel management workforce planning*

Using causal models to evaluate Force Generation options

Denis R. Shine[1], **Julia Knoll**[1] **and Thang Cao**[1]

[1.] *Defence Science and Technology Group*

Email: denis.shine@dst.defence.gov.au

Abstract: The Australian Army maintains a Force Generation system which allows for a portion of its forces to maintain a high level of readiness for operations while allowing for time to train and recuperate. The current Force Generation system, based on Plan Beersheba, has been in operation for approximately a decade, but the challenges posed by Accelerated Warfare and future Army modernisation programs require that the Force Generation system adapt also. Defence Science and Technology Group (DSTG) was engaged to rapidly assess the trade-offs between several Force Generation system options, and through wide stakeholder engagement, built the Force Generation Options Assessment Model, a hybrid Bayesian Belief Network and Utility model.

Stakeholders were engaged across the Army in a two-phase process. The first phase was model derivation, where we elicited the critical factors influenced by the Force Generation system, as well as their influences and linkages. This allowed for the construction of a causal model, albeit unpopulated. The second phase was model data collection, where the conditional probability tables were elicited for all factors from a wide range of Subject Matter Experts.

This paper describes the imperatives behind reviewing Army's Force Generation system, the DSTG approach for assessing Force Generation system options, the critical factors and measures which underpinned the assessment and the future developments planned for analytical conduct.

Keywords: *Army, Force Generation, causal models, Bayesian Belief Networks*

An evolutionary approach to balancing and disrupting real-time strategy games

Jacob Snell [a], **Martin Masek** [a] **and Chiou Peng Lam** [a]

[a] *School of Science, Edith Cowan University, Joondalup, Western Australia*
Email: j.snell@ecu.edu.au

Abstract: In most computer games, the level of challenge experienced by a player is dependent on a range of variable factors defined within the game environment. When the end goal of such games is entertainment, the variables are carefully tuned by the designers to achieve a sense of fair, balanced gameplay. For military force design and wargaming applications, where the purpose is to explore elements of a real scenario, the question turns to how the variables can be exploited so as to provide the maximum advantage, and to disrupt the balance in favour of a particular side. In this paper, an automated approach to explore the impact of game variables on game balance is presented and evaluated. Based on an evolutionary algorithm, the approach explores a user-defined set of variables in order to determine optimal combinations of variable values to achieve a defined level of game balance or game disruption. The approach also provides the ability of biasing the search towards a set of user-defined values of the game variables, providing insight into how the most disruption can be achieved with the least amount of deviation from an existing strategy.

Two scenarios were developed in a Real-Time Strategy game environment with a focus on verifying the developed approach. Both scenarios were adversarial, with two opposing teams, Red and Blue, with the goal of each team to eliminate the opposition. The level of balance/disruption for a particular set of Blue Team variables was measured as a function of the difference between a target blue win rate and the actual win rate, with a tuneable bias to favour solutions where the solution deviated the least from a 'fair' solution (where the Blue Team had the same strength as the Red Team).

The first scenario was designed so that both teams were evenly matched in terms of number of units. The scenario was used to explore how the game balance could be disrupted by manipulating variables associated with the Blue Team units. The second scenario was developed so that one team was given significantly more fighting units. This was to test if the approach was able to achieve a particular desired level of balance or disruption despite the starting balance skew.

A series of experiments were performed using the developed scenarios to evolve a set of game variables tied to the Blue Team to achieve a range of balance levels while the red team's variables were kept static. The experiments show that it is possible to use the developed approach to balance or disrupt the variables of a game so that the desired level of game balance is achieved. A separate series of experiments also showed that the evolution process could be biased to find game variables that required the smallest amount of change. This is particularly important for balancing video games where designers often prefer only to make slight changes to the variables of a game even when desiring a large difference in a game's balance.

Keywords: *Real Time Strategy game, game balancing, game disruption, evolutionary computing*

Visualisation Library: an accessible, extensible and customisable information visualisation suite for Defence Operations Research

April Melanie Tieu [a] **and Rebecca Ong** [a]

[a] *Defence Science and Technology Group*
Email: april.tieu@dst.defence.gov.au, rebecca.ong@dst.defence.gov.au

Abstract: Information visualisation is the translation of information into a pictorial or graphical form that assists in the identification of insights and the comprehension of data that cannot be inferred with statistics alone (Anscombe 1973). Effective visualisation is achieved through techniques, such as the use of icons, narratives and diagrams, that not only present information in a concise and coherent manner but, in doing so, reduce the cognitive load on the viewer, allowing more time to make informed decisions rather than attempting to interpret the visualisation (Huang et al. 2009). With the rise of big data, this practice is an essential part of many fields, particularly in Defence where vital decisions are made based on both quantitative and qualitative information.

Tools for creating information visualisation exist, such as Tableau (2003). However, due to the unique nature of Defence Operations Research (OR) data, standard tools for non-specialists are limited in use. In particular, they lack the customisability needed to create Defence-specific visualisations that show highly interconnected combinations of qualitative and quantitative information. Although there are tools that create high-value visualisations for Defence OR (Rempel and Young 2017), creating such tools are time consuming, involve specialist skills, and have minimum reuse value outside of their specific design requirements. There also remains an absence of a centralised place for information visualisation tools and resources aimed at both developers and non-developers, limiting Defence from fully utilising the benefits of custom information visualisations. To improve data-driven decisions and understanding of Defence data, these needs must be addressed.

Based on these needs, we created the Visualisation Library: a web-based tool that bridges the gap between information visualisation and accessibility, customisability and extensibility within Defence. It is hosted through the Knowledge Exploration Node (KEN), a web-based platform integrating web-applications for knowledge elicitation, data analysis and information visualisation.

The Visualisation Library categorises visualisations into five types: Connections, Hierarchies, Maps, Charts and Icons. Within each category, visual elements are modularised such that they are reusable and customisable within the KEN framework. Further, it is accessible; the web-based interface provides a platform to create custom information visualisations without the need to code, while the backend design provides ease of implementation for developers. It is also extensible; new functionalities, on top of built-in interactivity, can be easily added as required. Currently, the platform stores over 25 ready-to-use, Defence-specific icons, alongside the other visualisation types. Proof of concept of these features is demonstrated in a new qualitative data visualisation tool, the Network app, which we present as a case study.

The Visualisation Library is intended to allow all Defence personnel, regardless of their technical expertise, to create information visualisations tailored to their needs. By providing a centralised platform for information visualisation, this tool will enhance decision making in Defence.

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Keywords: *Information visualisation, visualisation, user interfaces, visual knowledge discovery*

Nesting data-driven robust multi-objective decisions for integrated precinct-scale energy–water system planning

G. Cardoso de Oliveira [a b], E. Bertone [a b], R. Stewart [a b]

[a] Systems Modelling Group, Cities Research Institute, Griffith Sciences, Australia
[b] School of Engineering and Built Environment, Griffith University, Gold Coast, Queensland, 4215
Email: glauber.deoliveira@griffithuni.edu.au

Abstract: Traditionally, water and energy planning for new building and retrofit projects are completed almost always separately at a precinct scale. To address this singular lensed focus, a novel data-driven robust multi-objective optimisation approach was introduced nesting long-term capital and short-term managerial precinct-scale energy–water system decisions for diversified Pareto-efficient investment portfolio selection through integrated planning. Attempting to generalise evidence-based integrated energy–water system plans, a parsimonious mathematical optimisation model was developed aiming at the simplest possible principled way to capture spatiotemporal energy–water interactions in real applications.

From a planning perspective, selection criteria were established with distinct technical, economic, and environmental dimensions. To support decision-making under uncertainty, a robust deterministic optimisation problem was formulated for reducing variable loads, system costs, carbon emissions, and water wastage in urban precincts. To enhance the overall energy–water system performance, desirable conflicting technoeconomic/environmental objectives were subject to hard coupling allocational/operational constraints, ensuring system reliability, balancing cost-effectiveness, and fostering resource sustainability.

Surrounding the built environment among candidate and built facility locations, the local energy–water distribution network was modelled envisioning a decentralised community microgrid to augment operational flexibility across controllable infrastructure assets. In this engineering domain, the optimisation problem was arranged into two substructures of a mixed-integer disciplined convex program, tackling the critical energy–water system sizing/scheduling tasks over the planning horizon. Different feasible generation/storage technologies can be suitably selected for the optimal sizing of distributed energy–water supply units that meet local site-specific requirements. The system scheduling is optimised to best utilise energy and water for resource-related use efficiency improvement, diminishing power consumption and associated electricity costs. To meet resource-related end uses, polygeneration schemes are dynamically simulated for matching energy–water supply-demand in realistic conditions, while reducing electrical, hydraulic, and thermal urban precinct building loads from powered cooling, heating, pumping, and lighting services.

Uncertainties inherent to energy–water demand and supply were explicitly characterised by parameterising representable random perturbation sets, which affect adaptive nested resource actions taken for robust optimal planning decisions. Formally, a global approximation method was tailored for an enhanced practice in integrated precinct-scale energy–water system planning activities and exercises. To obtain lower/upper bounds on optimal values of the multiple objectives defined for yielding substantial cost savings, load reduction, and carbon mitigation, a matheuristic outer/inner-layer problem decomposition procedure was implemented with an iterative cutting-plane solution algorithm calling scalable state-of-the-art solvers.

Computational experiments were proceeded to demonstrate the applicability of the proposed decision support framework. Demonstration cases were considered in prospective energy–water demand/supply scenarios, including extreme situations to minimise worst-case expected values for potential renewable energy penetration and nonpotable water exploitation. Pareto-optimal trade-offs are evaluated among desirable conflicting value-at-risk minimisation and return-on-investment maximisation objectives to determine the best integrated energy–water system plans at precinct scale, covering available retrofit projects to be chosen with appropriate financing options. Numerical results reveal considerable synergies between energy and water resources, unraveling significant non/monetary benefits for facility custodians. Moving towards sustainable urban precincts, the outlined adaptive nested dual data-driven robust multi-objective integrated water-energy system decision support framework is superior to traditional separate resource planning.

Keywords: *Precinct scale, urban planning, energy–water nexus, system integration, optimisation modelling*

SPARC – A generic portfolio optimization and visualization tool

Carolyn M. Chen[a], **Kendall Wheaton and Gregory van Bavel**[a]

[a] *Defence Research and Development Canada, Department of National Defence, Ottawa, ON, Canada*
Email: carolyn.chen@forces.gc.ca

Abstract: Strategic planning for long-term capital investments in defence is an important activity undertaken by the senior military and civilian staffs in defence organizations. The problem of selecting the best set, or portfolio, of investments to equip future forces is challenging and may be approached many ways. Portfolio optimization is one method that can be used to model a portfolio of defence investments (Harrison et al. 2020) under a variety of constraints. The Canadian Department of National Defence (DND) has developed a capital investment plan review process supported by a specialized visual analytics tool called VIPOR (Visual Investment Planning Optimization & Revision) that employs both portfolio optimization and interactive visualization (Rempel & Young. 2017). VIPOR was developed by Defence Research and Development Canada (DRDC) specifically for DND's capital investment program. DRDC has recently developed, in a collaboration with the National Research Council of Canada (NRC), a new portfolio analysis tool called SPARC (Strategic Portfolio Analyzer with Reconfigurable Components). SPARC is a generic portfolio optimization software with built-in visualization capabilities. The distinctive feature of this tool is that it utilizes generic data ingestion to provide portfolio optimization capabilities to a wider audience of planners.

In line with the generic capabilities, SPARC was designed to use .csv files for data input. These files contain information on the objective, resource use, and constraints needed for the optimization of a generic collection of initiatives or projects. Users are able to select from a small set of algorithms to suit their different analysis needs: (1) knapsack for selecting the best set of initiatives, (2) knapsack with portfolio constraint limit re-profiling, and (3) maximum coverage for portfolios that optimize requirements. Complex initiative/project scoring models can be implemented in Python or R. Results can be visualized in customizable plots, where the user can gain insights from viewing, manipulating and re-optimizing the data.

Interactive visualization is only practical in an analysis tool if the optimization calculations to identify sets of investments are performed in, at most, a few minutes. During the development of SPARC, three commercial solvers were evaluated using a typical capital investment knapsack example (nine variations of a capital investment problem with 300 major projects planned over a period of 40 years). The solvers were IBM CPLEX, the SAS Institute OR Module and The MathWorks Optimization Toolbox. All three solvers performed well and were selected for use with SPARC. The average solve time for CPLEX was 3 minutes, varying from a few seconds to 8 minutes. With tuning, SAS performed almost as well. The average solve time for MATLAB was 19 minutes making this solver acceptable for smaller portfolio problems.

Two fictional examples will be presented to show SPARC's interactive visualization capabilities. The first is an example of finding the best value for a capital investment plan with a large portfolio of potential projects over a 40-year time frame. The second example involves the prioritization of staff workloads in a fictional military headquarters where the demand for staff to manage new projects, manage current capabilities, and develop plans for future forces exceeds the capacity of headquarters.

The presentation will show how SPARC is used as an optimization-visualization platform where users are able to input, optimize, and view generic data. SPARC's interactive capabilities simplify the iterative process of creating and comparing solutions. This tool can be used by both analysts and decision makers to help inform and guide their decisions on complex problems such as the prioritization of capital investments or the allocation of scarce expertise to high priority tasks.

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Keywords: *Portfolio optimization, SPARC, knapsack, set cover*

EXTENDED ABSTRACT ONLY

Hybrid metaheuristics for channel scheduling

P. Corry [a] and **C. Bierwirth** [b]

[a]*School of Mathematical Sciences, Queensland University of Technology, Brisbane*
[b]*Department of Business Administration, Martin-Luther-Universität Halle-Wittenberg, Germany*
Email: p.corry@qut.edu.au

Abstract: In recent years, much attention has been given to the Berth Allocation Problem (BAP) in its many shapes and forms. More recently, the authors of this current study described the problem of scheduling ship movements in a channel, termed the channel scheduling problem (ChSP), and integrating this problem with the classic discrete BAP, which was termed berth allocation problem with channel restrictions (BAP-CR). The ChSP considers a channel connecting an open sea anchorage with a set of berths for loading/unloading ships. A channel consists of a series of channel segments, which either allow or forbid passing of oncoming vessels. Following ships are permitted to concurrently occupy the same channel segment, but must observe a minimum separation time constraint on entry and exit to the segment. For a given set of berth allocations and berth sequences, the problem is to schedule movements of ships through the channel to minimise channel access delays at anchorage and prior to berth departure (see Figure 1).

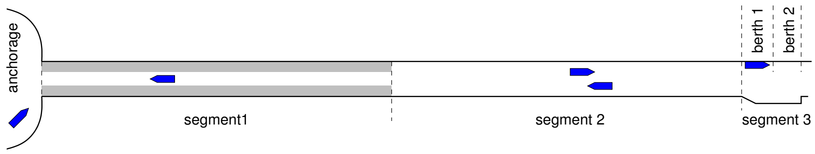

Figure 1. Illustration of a typical BAP-CR (Corry & Bierwirth (2019))

A mixed-integer program (MIP) was previously proposed in Corry & Bierwirth (2019), along with constructive heuristics to find solutions to ChSP and BAP-CR, both of which were demonstrated to be computationally challenging. Corry & Bierwirth (2019) showed the difficulty of solving BAP-CR exactly depended on a number of factors. As the number of vessels increases, the problem is more difficult to solve. However somewhat counter intuitively, reducing the number of berths makes the problem more challenging, since it increases the number of possible berth sequencing combinations. The arrival pattern of vessels has an influence, with more spread out arrivals resulting in faster solve times generally. The number of channel segments has a lesser influence on solve time.

The current study extends the previous work by exploring the hybridisation of the existing constructive heuristic with a simulated annealing metaheuristic (SA-CH), focusing on BAP-CR. The proposed SA-CH approach works by perturbing either a priority ordering of ship movements, or a vector representing berth allocations for each ship. The priority ordering is applied within the constructive heuristic to resolve channel conflicts. It is a simple solution representation amenable to perturbation operators within metaheuristics. Every solution generated within SA-CH is constructed by applying the constructive heuristic (along with the current berth allocation vector), with ship movements inserted to the schedule in the order prescribed by the priority ordering. The priority ordering influences which ships get priority over others when resolving channel conflicts. For the current study, we focus on BAP-CR problems with 30 ships, 10 berths and 2 channel segments which are challenging to solve as a MIP. The computational study demonstrates that SA was able to outperform a Genetic Algorithm implementation of the same priority order constructive heuristic approach. With a 10 minute time limit, SA also demonstrated generally superior solution quality compared to CPLEX, even when 32 CPU cores were allocated to the solver, compared with SA which ran on a single thread.

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Keywords: *Berth allocation problem, channel scheduling, ports, metaheuristics*

The use of technology foresight methods for emerging and disruptive technology assessment symposia

P. Dexter [a], **M. Burnett** [a] **and D. Tailby** [a]

[a] *Defence Impacts of Emerging Technologies, Joint and Operations Analysis Division, DSTG*
Email: patricia.dexter@dst.defence.gov.au

Abstract: Defence and National Security agencies increasingly require a comprehensive and evidence based understanding of emerging and potentially disruptive technologies, to avoid strategic surprise, protect capability advantage and exploit future opportunities. Systematic analysis into emerging technologies and their capabilities has become progressively important to inform strategic risk assessments, force design, protection of sensitive technologies, innovation investment and National Security decisions. The use of established foresight methods in this analysis helps to ensure that government policies and decisions are informed by the best scientific evidence and strategic long-term thinking. Futures methods used in the *Strategic Futures Project* in Defence Science and Technology Group (DSTG) include horizon scanning, trend analysis, scenario planning and Delphi. The outcomes support a range of foresight analysis goals:

- An ability to understand the driving forces affecting a future military capability.
- A means of achieving consensus amongst a range of stakeholders about the emerging science and technology (S&T) issues in an area, and their potential impact.
- Building awareness of the advances across a range of S&T areas, including the key players and institutes, and main military capability impacts.
- An ability to systematically explore the transformative or disruptive implications of large, active and developing S&T areas such as artificial intelligence or human biotechnologies, out to 20 years into the future.

The Emerging Disruptive Technology Assessment Symposia[1] (EDTAS) analytical campaigns tackle the last of these goals. EDTAS brings together internationally recognised and local academics, industry and Defence leaders to explore and shape the long-term vision for an expansive technology area. The EDTAS program is funded by, and the themes drawn from, the Next Generation Technology Fund[2] (NGTF) and the STaRShots[3]. The first EDTAS campaign in 2015 explored Trusted Autonomous Systems (TAS) and a further seven have been conducted since on topics ranging from Advanced Materials and Manufacturing to Remote Undersea Surveillance.

Collaborative foresight design underpins the two key activities, which are working symposia: an open symposium scoping the technology opportunities and a classified symposium exploring military implications. This aims to build awareness across diverse stakeholders and experts both of the current state of the topic and of the future implications of technological developments. The campaign of analysis broadly follows a Scan-Orient-Explore-Report methodology. *Scan and Orient* scope and bound the problem and interview thought leaders producing a document to seed discussion, which participants have prior to the key activities. The *Explore* phase comprises the key activities where participants are engaged in experiential futures workshops designing technology concepts for the future and then exploring implications for the ADF. Previous EDTAS campaigns have informed and shaped research programs with outcomes including establishment of the TAS Strategic Research Initiative (and subsequent Commonwealth Research Centre), new research funded by NGTF under the Enhanced Human Performance theme, and changed paradigms in design and structure for the space domain to leverage broader creative research collaborations.

[1] https://www.dst.defence.gov.au/events/emerging-disruptive-technology-assessment-symposium-edtas
[2] The NGTF is a forward-looking program focussing on research and development in emerging and future technologies for the "future Defence force after next". https://www.DSTG.defence.gov.au/nextgentechfund
[3] Science, Technology and Research (STaR) Shots are challenging, inspirational and aspirational S&T missions that will align strategic research to force structure priorities. https://www.dst.defence.gov.au/strategy/star-shots

Keywords: *Foresight, Futures methods, Force design, EDTAS*

Optimisation of power system shutdown policies to reduce bushfire risk

Simon Dunstall [a], **Elena Tartaglia** [a], **Carolyn Huston** [a] **and Alec Stephenson** [a]

[a] *CSIRO Data61, Melbourne, Victoria, Australia*
Email: simon.dunstall@csiro.au

Abstract: Electricity corporations in areas prone to grass and forest fires are obliged to undertake a range of measures that lead to reduced rates of fire ignition especially when the consequences of fire are high. Turning off the electrical supply (to be referred to here as *de-energization*) when the fire weather conditions are at their most dangerous is one of the risk reduction methods at the disposal of electricity businesses, and it is used in Australia and in North America. De-energization is an action that comes at substantial cost for the community and which also introduces new health and safety risks. De-energization is therefore a risk reduction tool to be used intelligently and rather sparingly. The Eastern Australian bushfires of Ash Wednesday 1983 prompted infrastructure and operational policy changes in the affected states, and de-energization was a significant part of the South Australian response. Amongst the Australian states it is only in South Australia that de-energization of the power system to eliminate fire ignition risk is utilised at present. De-energization is an operational management decision by network managers. In some fire seasons de-energization has not been applied at all, whereas in others including the 2019-2020 "Black Summer" fire season the power system was de-energized for hundreds of thousands of customer-hours. Whether de-energization is a good tactic for risk reduction is hotly debated in the Australian electricity industry. Risk quantification and de-energization policy optimisation can assist in informing this debate, as a side-effect of the primary aim which is to optimise the de-energization policy in regions where it is considered appropriate to do so.

An optimal de-energization policy delivers outcomes lying on a Pareto frontier between risk reduction benefit and de-energization cost. Cost in this sense is commonly measured in terms of total customer-hours off supply multiplied by the dollar value that the electricity business associates which each customer hour. This dollar value of lost supply may change from year-to-year and is commercially sensitive information. Risk reduction benefit is typically expressed as an avoided expected economic loss (which might or might not include quantification of human and ecosystem negative impacts) and therefore also has a monetary unit. A de-energization policy consists of pre-determined decisions about which parts of the network to de-energize under which observed fire weather conditions. For example, a component of a policy might be that certain electrical *feeders* are de-energized when the fire danger rating is *extreme* or *catastrophic* and the mean wind speed exceeds 45 km/h. This policy-based approach can be viewed in contrast to a dynamic approach where risk and cost are predicted in near real time and de-energization decisions flow from this. A dynamic approach is theoretically desirable but extremely challenging to operationalize in practice.

Data science can be used to quantify the costs and benefits of power outage and ignition risk reduction at particular times at specific parts of the network. Our chosen path to formulating an optimal de-energization policy is to use such information and solve an optimisation problem in "backcast" mode over historically observed meteorology and fire risk. The decision variables in this problem relate to which subset of several weather-related criteria will be applied to each distinct part of the network that can be de-energized. Alternative policies are constructed with different cost budgets, and strategic decision makers can select their preferred trade-off between risk reduction and cost with reference to their overall risk appetite. We present optimal (integer programming) and heuristic (list-based) algorithmic approaches for forming the de-energization decision policies. These methods use large volumes of data that result from the sampling of representative meteorological data streams, the estimation of ignition and major fire likelihood at every network location, and large-scale fire simulation experiments. We also describe how the optimisation algorithms and results have been used collaboratively with fire risk managers to determine operational procedures for electricity network risk management in upcoming fire seasons.

Keywords: *Operations research, optimisation, wildfire, electricity supply*

Forecasting sales with Bayesian networks: a case study of a supermarket product in the presence of promotions

M. Hamza [a], **M. Abolghasemi** [a] **and A.O. Alvandi** [b]

[a] *Department of Data Science & AI, Monash University.*
[b] *Department of Human Centred Computing, Monash University*
Email: mham0030@student.monash.edu, mahdi.abolghasemi@monash.edu and abraham.oshnialvandi@monash.edu

Abstract: Sales forecasting is the prerequisite for a lot of managerial decisions such as production planning, material resource planning and budgeting in the supply chain. Promotions are one of the most important business strategies that are often used to boost sales. While promotions are attractive for generating demand, it is often difficult to forecast demand in their presence. In the past few decades, several quantitative models have been developed to forecast sales including statistical and machine learning models. However, these methods may not be adequate to account for all the internal and external factors that may impact sales. As a result, qualitative models have been adopted along with quantitative methods as consulting experts has been proven to improve forecast accuracy by providing contextual information. Such models are being used extensively to account for factors that can lead to a rapid change in sales, such as during promotions. In this paper, we aim to use Bayesian Networks (BNs) to forecast promotional sales where a combination of factors such as price, type of promotions, and product location impacts sales. We choose to develop a BN model because BN models essentially have the capability to combine various qualitative and quantitative factors with causal forms, making it an attractive tool for sales forecasting during promotions. Also, BNs are graphical tools that allow us to visualize the effect of an observed node on all the other nodes of the network. This can be used to adjust a company's promotional strategy in the context of this case study. We gather sales data for a particular product from a retailer that sells products in Australia. We develop a BN for this product and validate our results by empirical analysis. We show that the BNs are superior in predicting overall average weekly sales and average weekly sales during catalogue promotions to the company's forecasts in the case study. This paper confirms that BNs can be effectively used to forecast sales, especially during promotions. In the end, we provide some research avenues for using BNs in forecasting sales.

Keywords: *Forecasting sales, Bayesian networks, promotional sales, retailers*

Risks of AI: technical, ethical and existential

Jacob I. Koehler [a]

[a] *Joint & Operations Analysis Division, Defence Science and Technology Group, Australia*
Email: jacob.koehler@dst.defence.gov.au

Abstract: Artificial Intelligence (AI) has a reputation as a risky technology. It is new, rapidly advancing, and has been the subject of much hype, with a history of over-promise and under-delivery. This paper presents the outcome of a literature study into the risks associated with the employment of AI across a wide range of use cases and explores the moral and ethical issues in the application of AI.

Managing technical risks are an important part of any development process. AI systems pose a unique risk as they operate in complex environments that can never be completely known, and are often designed to evolve their response with new stimuli. The inherent nature of AI is that their response to stimuli may be unpredictable or have poor decision traceability, which can limit AI's effectiveness when teaming with human actors or contribute to moral and ethical risks (Chen et al., 2018). AI's ability to adapt to challenges and invent novel solutions is a key reason for its use, therefore improving decision traceability and transparency of AI systems is essential to mitigate the unique technical risks (Standards, 2019).

Application of AI in many circumstances poses moral and ethical risks. The effects of widespread employment of AI cannot be known. Traceable and transparent decisions by AI will facilitate greater scrutiny and trust in AI but some argue that AI, as a non-human actor, should not be able to make decisions that will impact on humans (Asaro, 2013). Requiring a human for key decisions reduces the risk to humans, but impinges upon the autonomy of AI systems (Roff, 2014). Ultimately, lawmakers need to address whether AI can be trusted to make decisions for humans.

AI has been hyped since its inception as a possibly civilisation-ending technology with the images of killer robots led by a super-intelligent artificial intelligence spurred on by popular culture. The concept of an intelligence so far beyond human it cannot be matched relies on several assumptions being made, but even current AI systems have potential to be a disruptive force. AI can also be developed at a relatively low cost and be deployed to cause disruption in critical areas that rely on a connection to the outside world via the internet (Brundage et al., 2018). Use of AI can be somewhat controlled through treaties and research agreements, but researchers need to carefully balance the benefits of openness with the risk of access by malicious actors.

AI is a disruptive technology with a propensity to act in unexpected ways. Traceability and transparency reduce technical and ethical risks but must be balanced against reducing AI's ability to evolve. As with any disruptive technology, malicious actors (including the AI itself) may misuse AI systems, so ready access to advanced AI systems must be balanced against the risks posed by malicious actors. Striking this balance has particular implications for Defence, as late adoption may result in a military disadvantage while insufficiently researched AI may inadvertently cause harm.

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Keywords: *Artificial intelligence, ethics, risk analysis*

Representing Defence Capability Portfolio as Set-Union Knapsack

Carlos Kuhn [a], Gregory Calbert [a], Terence Weir [a], Ivan Garanovich[a]

[a]*Joint and Operations Analysis Division, Defence Science and Technology Group, Department of Defence, Canberra, ACT 2610, Australia*

Email: terence.weir@dst.defence.gov.au

Abstract: In large organisations and companies, making investment decisions is a complex and challenging task. In the Aus-tralian Department of Defence (Defence), the complexity is even higher because defence capabilities are a public good and do not have a financial return *per se*. Defence needs to select projects in readiness to respond to a gamut of military and national security challenges. A project's comparative ability to respond to such challenges at a particular time forms its value. Investment decisions are constrained by a limited annual budget. Projects that are chosen to be funded, with the aim of maximising value, form Defence's investment portfolio. To support this selection problem, a mathematical tool to schedule projects and maximise value while satisfying budget constraints is required to aid decision makers.

As part of Defence's portfolio design activities in 2021, subject matter experts (SME) developed a range of capability options to satisfy strategic and operational requirements into the future. Options with common objectives were grouped into families; each option could consist of multiple projects and projects could be shared across options. Each project had a given cost profile over time, and there was a given budget ceiling in each year of the time horizon under consideration. SMEs also identified a project's starting time window and relative year of effective delivery. Only a single option at most was chosen from each family. Supported by a Bayesian belief network, each option was valued over time. The sum of all option values when each became effective was used to determine the fitness of a potential investment portfolio.

The grouping of projects into options creates challenges to an optimisation problem formulation because the fitness function is applied to the options while the budget constraints are applied to projects. Mathematically this is a complex variation of the Knapsack problem (Mathews 1896) known as set-union knapsack problem (SUKP).

In this work we mathematically define Defence's investment portfolio problem as a SUKP. Unlike previous dynamic programming (Goldschmidt et al.1994) or heuristic approaches (Arulselvan 2014, Wu and He 2020), we present a novel way to linearise the model as an Integer Linear Programming (ILP) problem. This linear model was developed as the optimisation engine of the New Investments to Risked Options (NITRO) portfolio selection tool developed by the Defence Science & Technology Group (DSTG) for Defence force design activities in 2021. Relaxation of the ILP is guaranteed to be solved in polynomial time and generates at least a known number of integer solutions, whereas there is no guarantee for this via the dynamic programming approach and heuristic approaches require tuning of parameters for different problem sets. This makes the linearised model attractive as its implementation can be set up as a plug-in for users so as not to require extensive user interaction.

The model is implemented in the Python package called PuLP calling data stored in a Microsoft SQL Server database and presents the results in a browser-based user interface. PuLP can call several linear solver's application programming interface, such as GLPK, COIN CLP/CBC, IBM CPLEX, and GUROBI. After comparing the performance of several solvers, we chose GUROBI in the production server. The implementation of the new model and solver enable the rapid execution of exact solutions to the Defence investment portfolio problem.

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Keywords: *Portfolio optimisation, Integer Linear Programming, Python*

Using mixed integer-linear programming to manage a military aircraft fleet to life-of-type

David. O. Marlow [a] **and Robert F. Dell** [b]

[a] *Joint and Operations Analysis Division, Defence Science and Technology Group, Fishermans Bend Vic 3207, Australia*
[b] *Operations Research Department,, Naval Postgraduate School, Monterey CA 93943, USA*
Email: david.marlow@dst.defence.gov.au

Abstract: Military aircraft fleets can remain in service for decades. The United States Air Force (USAF) still operates a fleet of B-52 bombers, despite having been originally introduced in the 1950s. Typically a fleet life is of the order of 20-30 years. Once an aircraft reaches its life-of-type (often measured in airframe or flying hours), it is withdrawn from service. Ideally, individual aircraft in the extant fleet are progressively retired from service while a new replacement fleet is progressively phased into service. This allows for some continuity of capability during the transition.

A military aircraft fleet is expected to perform all tasks required of it at all times during its life, up to and including life-of-type. Therefore, it is important that fleet planners and managers ensure balanced usage rates across the fleet. Otherwise, individual aircraft may have to be retired from service early, having reached their individual life-of-type before the fleet reaches its retirement date. This in turn will reduce the ability of the fleet to meets its requirements in the latter years of the fleet life. Conversely, individual aircraft may still have available airframe hours remaining when the fleet reaches its retirement date. This too is undesirable. Such instances of sub-optimal fleet management have non-trivial costs: a recent example for a sub-fleet of USAF A-10 Thunderbolts estimated those costs in the tens of millions of dollars (Newcamp et al., 2019).

In this work we present a mixed integer-linear program (MIP) for optimal management of a fleet of military aircraft over a multiple-year time horizon, up to life-of-type. The model includes several features relevant to fleet management at such timescales. These include: depot maintenance inductions with induction windows, modification programs (that can be undertaken following various depot maintenance types, or on standalone modification lines), aircraft deployments to operational areas; exercises (requiring a specified number of aircraft at specified times of year); and stand-down periods (where aircrew and maintainers do not work). Model decisions therefore include: when to induct an aircraft into depot maintenance; which aircraft to deploy or send on exercises; how to allocate aircraft flying hours, and how to schedule a modification program.

The model can be run at various timescales with various time steps, depending on the scenario. Typically the time step is weekly or monthly. The model can also cater for a single objective or multiple objectives, representing the many competing priorities of fleet planners. These objectives may include: meeting availability targets; meeting annual flying targets for a fleet and each squadron in the fleet; flying aircraft into depot maintenance (when these services are triggered by both elapsed time and flying hour intervals); and meeting the pre-determined targets for usage rates at the end of the time horizon. The user can weight these objectives according to fleet planning priorities. Alternatively, the model can be solved in a heuristic manner. This involves solving for the most important priority/priorities first, and then progressively solving for the others in priority order while using the results from the previous solution as fixed inputs.

We demonstrate the model's capability with some examples, using small fleet sizes typical of those of the Royal Australian Air Force (but needing tens of thousands of constraints and decision variables). These include general fleet planning applications to meet multiple objectives, and scheduling a major modification program so as to best meet availability targets. We show the ability of the model to conduct what-if or trade-off analysis: e.g. modification program completion times against fleet availability rates. Such information can be provided by a fleet planner to a fleet commander to help guide decision-making based on extant requirements. Future work will likely consider alternative formulations and solution techniques (e.g. metaheuristic approaches).

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Keywords: *Military aircraft fleet management, mixed integer-linear programming, life-of-type*

The Open Maritime Traffic Analysis Dataset

Martin Masek [a], **Chiou Peng Lam**[a], **Travis Rybicki**[a], **Jacob Snell**[a], **Daniel Wheat**[a], **Luke Kelly**[a], **Damion Glassborow**[b], **Cheryl Smith-Gander**[b]

[a] *School of Science, Edith Cowan University, Joondalup, Western Australia,* [b]*Defence Science and Technology Group, Department of Defence, Australia*
Email: m.masek@ecu.edu.au

Abstract: Ships traverse the world's oceans for a diverse range of reasons, including the bulk transportation of goods and resources, carriage of people, exploration and fishing. The size of the oceans and the fact that they connect a multitude of different countries provide challenges in ensuring the safety of vessels at sea and the prevention of illegal activities. To assist with the tracking of ships at sea, the International Maritime Organisation stipulates the use of the Automatic Identification System (AIS) on board ships. The AIS system periodically broadcasts details of a ship's position, speed and heading, along with other parameters corresponding to the ship's type, size and set destination.

The availability of AIS data has led to a large effort to develop automated systems which could identify and be used to prevent undesirable incidents at sea. For example, detecting when ships are in danger of colliding, running aground, engaged in illegal activity, traveling at unsafe speeds, or otherwise attempting manoeuvres that exceed their physical capabilities. Despite this interest, there is a lack of a publicly available 'standard' dataset that can be used to benchmark different approaches. As such, each new approach to automated maritime activity modelling is tested using a different dataset to previous work, making the comparison of technique efficacy problematic.

In this paper a new public dataset of shipping tracks is introduced, containing data for four vessel types: cargo, tanker, fishing and passenger. Each track corresponds to a leg of a vessel's journey within an area of interest located around the west coast of Australia. The tracks in the dataset have been validated according to a set of rules, consisting of journeys at minimum 10 hours long, with no missing data. The tracks cover a three-year period (2018 to 2020) and are further categorised by month, allowing for the analysis of seasonal variations in shipping. The intention of releasing this dataset is to allow researchers developing methods for maritime behaviour analysis and classification to compare their techniques on a standard set of data.

As an example of how this dataset can be used, we use it to build a model of 'expected' behaviour trained on data for three vessel categories: cargo, tanker, and passenger vessels, using a convolutional autoencoder architecture. We then demonstrate how this model of ship behaviour can be used to test new data that was not used to build the model to determine whether a track fits the model or is an anomaly. Specifically, we verify that the behaviour of fishing vessels, whose movement patterns are quite different to those of the other three vessel types, is classified as an anomaly when presented to the trained model.

Keywords: *Maritime Track Dataset, Automatic Identification System (AIS), anomaly detection, machine learning*

EXTENDED ABSTRACT ONLY

The role of technology foresight in strategic decisions

R. Hales [a], M. McDonald [a], M. Burnett [a] and D. Tailby [a]

[a] *Defence Impacts of Emerging Technologies, Joint and Operational Analysis Division, Defence Science and Technology Group, Australia*
Email: ryan.hales@dst.defence.gov.au

Abstract: The Defence Strategic Update 2020 articulated the need for Defence to identify, respond to, and manage emerging and disruptive technologies that pose potentially significant impacts to achieving the Defence mission. Understanding technology trends and opportunities allows for protection against the strategic surprise from emerging and disruptive technologies, and ensuring access to technology driven advantage. The academic and commercial sectors are driving forces behind technology emergence and evolution. Seeking out opportunities to exploit scientific breakthroughs and conceive novel applications within different environments can lead to potential commercial or national advantage. This paradigm shift has revolutionised time-to-market expectations, and in many cases, reduced the cost of advanced technologies. It has also accelerated and expanded the already competitive technological marketplace.

The *Strategic Futures Project* in Defence Science and Technology Group (DSTG) conducts technology foresight to inform decision makers of the emerging, critical and potentially disruptive technologies most likely to impact or influence the Australian Government, Defence and national security. It focuses on technology areas that have the potential to be game changing, pervasive or critical to the national interest.

The *Project* uses structured methods (Glenn and Gordon 2009) to discover, assess and communicate emerging, critical and disruptive technologies. This provides insights into technological developments now that enable early preparations for possible futures. Engaging with uncertainty ensures decision makers have the best available advice to make strategic decisions regarding innovation, science and technology investment. The foresight methods include:

Discovery: Discoveries can be led by data analytics, or through the gathering of intelligence on technology areas of interest. Sources include literature, patents, venture capital and science and technology news. Natural language processing, feature extraction, trend monitoring and machine learned classification processes are used to filter and sort a vast array of potential technologies down to those that are relevant to the national interest. Reviews, Red Teaming and critical reflection by subject matter experts are key to achieving relevant results.

Assessment: Collaborative expert elicitation methods are used to develop an understanding of the scientific, technical, political, social and economic impacts. These elicitations harness the 'brains trust' of government, industry and academic participants into a structured, yet highly creative and interactive setting. An example is the Emerging Disruptive Technology Assessment Symposia (EDTAS). This provides a shared understanding, improved networking and can yield innovative ideas on technology disruption.

Communication: Succinct and targeted communications are used to share creative, yet realistic, scenarios of how technologies may converge and impact the future. An example output are technology cards where potential applications are presented over a timeline. These can assist strategic decision makers absorb and compare a large variety of technologies, and influence the agendas for Defence's Integrated Investment Program (IIP) and innovation initiatives (https://business.gov.au/CDIC/Innovate-in-defence).

The Defence technology foresight methodology is predicated on diverse discovery and assessment, and targeted communications, to ensure decision makers have the advice to hedge and shape future uncertainty.

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Keywords: *Foresight, horizon scanning, futures methods*

Measures to analyse sustainability in military workforce structures

C. Pike [a] and W. Moran [b]

[a]Joint and Operations Analysis Division, Defence Science and Technology Group, Fishermans Bend, Victoria
[b]Department of Electrical & Electronic Engineering, University of Melbourne, Parkville, Victoria
Email: Cameron.Pike@dst.defence.gov.au

Abstract: For defence services to provide effective capability, it is important that enough suitably qualified personnel are available at the right times. Essential to this, is a workforce structure that *sustainably* meets the personnel requirement. Specifically, an adequate number of positions in the different ranks is needed, as well as sufficient promotions and recruitment to sustain those positions over time, given the constraints on the workforce. In this paper, we mathematically explore the relationship between these parameters, describe how to determine whether a workforce structure is sustainable or not, and detail what changes may need to be made to achieve a healthy structure.

Here, *sustainability* means that the requirement profile — the number of positions in each rank at each time — can be achieved without excesses or shortfalls of personnel. We critique a simple linear programming (LP) optimisation formulation that was applied to Royal Australian Navy (RAN) test problems, and the unexpected results that it produced. In particular, it resulted in large oversupplies in lower ranks early in a testing period of 20 years. By using a cost function that penalised oversupply and undersupply with different weightings, we found that such oversupplies were necessary in order to avoid significant shortfalls of personnel in higher ranks and later years.

This provided the motivation for the main contribution of this paper: an exploration of *why* the oversupply was necessary and equations that could assist workforce planners to quantify the magnitude of this oversupply. This involved assessing how specific factors play a role in the sustainability of workforce structures. Back-propagation of required numbers of personnel through the ranks provided the necessary number of promotions at each rank and time in order to achieve that requirement. We refer to this number of promotions as the Required Production Number (RPN). An analysis of the distribution of time in rank permits calculation of how many promotion-eligible personnel could be produced at each rank and time. We refer to this number of producible personnel as the Suppliable Production Number (SPN).

When the RPN exceeds the SPN, one of two functionally equivalent situations has to happen to avoid future shortfalls in other ranks as predicted by the model: oversupplying a rank or increasing the requirement of a rank. We quantify the extent to which the requirement needs to be increased. Conversely, when the RPN is less than the SPN, the requirement can be met without excesses or shortfalls of personnel, but personnel will spend longer in a rank before promotion. Calculations to quantify the expected time to promotion are also described. This is an important consideration as personnel waiting too long for promotion may result in decreased morale and an increase in personnel leaving the workforce.

These simple and practical measures allow workforce planners to draw insights into their workforce structure. In particular, they can determine whether and why the requirement in particular ranks is inadequate to supply higher ranks and assess whether and why personnel are spending excessive amounts of time in ranks before promotion. This contrasts with LP optimisation results, which can show these effects, but not easily and directly explain how the workforce parameters influence them. We also see in this work that two different requirements emerge: the *functional requirement*: the number of personnel the defence service needs to operate, and the *structural requirement*, which is the workforce structure needed in order to ensure that the functional requirement can be sustainably met, and that defence capability is maintained.

Keywords: *Workforce planning, workforce structure, military workforce, force structure, sustainability*

EXTENDED ABSTRACT ONLY

Decision support to reduce the risks associated with combustible cladding fires

Elena Tartaglia [a], Simon Dunstall [a], Carolyn Huston [a], Andreas Duenser [b] and Ulrich Engelke [c]

[a] *CSIRO Data61, Melbourne, Victoria, Australia*
[b] *CSIRO Data61, Sandy Bay, Tasmania, Australia*
[c] *CSIRO Data61, Kensington, Western Australia, Australia*
Email: elena.targtaglia@csiro.au

Abstract: *Expanded Polystyrene* (EPS) and *Aluminium Composite Panel* (ACP) have been popular materials for the exterior walls of commercial and multi-tenancy residential buildings in recent decades. Unfortunately it has become apparent over time that EPS and ACP wall cladding is typically combustible. The Grenfell Tower fire in London during 2017, in which 72 lives were lost, has highlighted the danger of such combustible cladding on residential buildings. In Victoria, combustible cladding fires have not led to fatalities but there have been significant events including the "Lacrosse" and "Neo" building fires in the Melbourne CBD in 2014 and 2019 respectively. Recognition of the risk to life and property has led the Victorian Government to establish the agency *Cladding Safety Victoria* and allocate over $0.5B in funding for the removal of combustible cladding from privately-owned multi-tenancy residential buildings (*Class 2 buildings*) in CBD, suburban and regional settings. This quantity of funding is generous yet not sufficient for fully removing combustible cladding from every Class 2 building in the state. Furthermore, the removal of cladding requires specialist expertise and resources in addition to careful assessment and planning, so is subject to significant capacity constraints. This means that not all risk can be addressed, some risk will remain in place for an extended period of time, and optimisation of the sequence of risk retirement is important.

For vegetation fire (in grasslands and forests) the simulation of fire spread has proven to be practical and quantitatively reliable for risk-aware decision-making at various spatial and temporal scales. By contrast, the simulation of building fire and its threat to human life relies on building-specific and complex data, some of which is extremely difficult to measure or estimate. Simulation systems that can be applied in a practical manner to a state-wide program of building rectification are elusive. The modelling and quantification of ignition likelihoods in the wildfire context is also a simpler proposition compared to building wall cladding combustion. This leads us to take a relative risk approach to residential building fires, where the focus is on finding the priority order of buildings for cladding removal, rather than quantitatively estimating the value of risk for buildings with combustible cladding. It also leads us to rely strongly on expert judgement of (relative) building fire consequences and the likelihood that ignitions propagate into cladding systems.

In collaboration with Cladding Safety Victoria the authors have developed methods for establishing a priority order of buildings for cladding removal. These methods harness expert judgement in a manner informed by understandings about human choice and cognition from psychological sciences. The methods also make use of the familiar notions of "precedence networks" and "dominance rules" from the project management and Operations Research literature. We exploit humans' ability to make reliable and repeatable pairwise relative judgements (in this context, about fire propagation and risk to life associated with building fire) and directly embed this elicitation process, via "human in the loop" software, within the construction of a tree-structured network expressing the relative unfavourability of different combinations of macro-scale building attributes that heighten fire risk (such as the type of cladding and the ease of emergency egress). By way of this process the network captures a series of relatively simple "facts" about priority and risk precedence. These facts combine to deliver a rich and systematic view of relative risk. A building priority order directly results from the network, and this order is complete, logically consistent, fully explainable with reference to the "facts". It is also generated without resort to weights or parameter values that can be contested by alternative experts with different preferences, utilities and opinions. The risk prioritization methods have been used in practice to promote buildings for cladding removal, establish acceptability thresholds for alternative solutions to full removal, and assist decisions that are made as further buildings with combustible cladding are put forward for assessment over time.

Keywords: *Operations Research, decision support, structure fire, risk prioritization, expert elicitation*

Modelling the ACT stamp duty and rates system using a housing microsimulation model

Hai Anh La, Yogi Vidyattama, Jinjing Li and Robert Tanton [a]

[a] *National Centre for Social and Economic Modelling, University of Canberra, Bruce, Australia*
Email: robert.tanton@canberra.edu.au

Abstract: In 2012, the ACT Government began a 20-year program to modernise the Territory's taxation system. This reform program has broadened the tax base by moving towards replacing inefficient taxes, such as stamp duty and insurance duty, with a broad-based land tax through the general rates system.

In 2019, the ACT Government commissioned NATSEM to investigate the impact of these reforms on the distribution of incomes across the Territory. This analysis used a microsimulation model of housing choice in the ACT, which created a baseline where the current ACT rates and stamp duty are applied, to compare with a counterfactual case where the regulations without the tax reform are employed.

The 2009-10 and 2011-12 Surveys of Income and Housing (SIHs) and the 2011 Census were used to generate a synthetic population for the ACT before the reform and then use data from the ACT government to determine what the ACT would have looked like now without the reforms. Other data from the Australian Bureau of Statistics (ABS) and other sources were also used to derive projections of what the ACT would have looked like if reform hadn't happened.

There were two research questions answered using this model:

1. What has been the impact of tax reform on different household types and cohorts, taking into account available concessions and deferral programs? and

2. What has been the impact of tax reform on the progressivity and equity of the ACT tax system, considering the incidence of property purchases by households with different levels of income and wealth?

Our modelling found that the new policy increased sales of properties for most groups; however the modelled price increases then reduced the extent of this increase.

With the property price change, all homeowners spend more on housing, possibly because of higher rates, and the stamp duty being paid on a more expensive property; and all renters who purchase in the period are better off, due to lower stamp duty, and not having to pay higher rates until they purchase.

We also find that low income families were paying less on stamp duty and rates as a proportion of the total stamp duty and rates paid under the new system compared to the old system. For rates, the highest income quintile was the only quintile paying more as a proportion of the total rates paid; and for stamp duty, the second two highest income quintiles were paying more as a proportion of the total stamp duty paid. Generally under the new system and considering spending on rates and stamp duty combined, lower income families and high income families are slightly worse off; while middle income families, who are probably benefitting from the stamp duty decreases, are better off.

Our analysis also finds that there are 1,599 additional first home buyers if there was no price increase as a result of the new policy and that this reduces to 1,053 under a 1.7% average price increase. This result for first home buyers is mainly driven by the deposit and income requirements used in the model.

Keywords: *Demographic modelling, housing tax, microsimulation*

An economic-modelling framework to assess the impact of population-wide preconception carrier screening for genetic disease

Lee, Evelyn[a], Shrestha, Rupen[a] and Schofield, Deborah[a]

[a] *Centre for Economics Impacts of Genomics Medicine, Macquarie University, 2109, Australia*
Email: evelyn.lee@mq.edu.au

Abstract: Children with genetic disease (GD) such as spinal muscular atrophy incur substantial costs to the family and healthcare system due to the chronic and early-onset nature of the GD. Preconception carrier screening (PCS) offers the possibility of averting GDs by identifying at-risk couples and enable them to make reproductive choices such as in-vitro fertilisation with preimplantation genetic diagnosis (IVF-PGD) or abstention from reproduction. This could potentially reduce healthcare utilisation and cost attributed to GDs and improve the life of that child and their family.

We describe a modelling framework of an ongoing study which aims to assess health and economic impact and the cost-effectiveness of offering population-wide PCS for genetic diseases to inform public funding decision. Specifically, we aim to evaluate the impact of PCS on reproductive decisions.

A microsimulation model is constructed using the 2016 Australian Census data as the base population and then applies a series of probabilities (e.g., carrier rate, incidence of babies with GD) and costs (e.g., cost of PCS, genetic counselling, diagnostic and follow-up) sourced from published data.

Microsimulation is a powerful technique that has the ability to capture the complexity and heterogeneity of children born with a genetic disorder. Therefore, this modelling approach will enable a more effective assessment of the impact of PCS and IVF-PGD on the prevalence of severely disabling or fatal heritable genetic disorder and quantify the health, economic and social impacts on families, government and society.

In this economic framework, the impact of population-wide PCS and IVF-PGD will be measured by reduction of GD cases, additional life-years and the cost-effectiveness is measured using incremental-cost per quality-adjusted-life-years gained from GD prevented.

Keywords: *Preconception carrier screening, genetic disease, cost-effectiveness, economics, microsimulation*

Financial stress and the social security settings – an optimal modelling approach

Ben Phillips

Centre for Social Research and Methods, Australian National University, Canberra, 2600, Australia
Email: ben.phillips@anu.edu.au

Abstract: Australian social security system spends around $120 billion dollars in cash transfers to Australian households each year. This money provides a safety net for around 5 million Australian's most of whom have little or no other regular income source due to age, incapacitation, caring responsibilities or unemployment. Payments to these persons do vary substantially as do their financial requirements.

This paper considers the latest trends in financial stress and poverty through recent decades but also through the COVID-19 period to better understand the emerging trends and the current state of financial stress and poverty for different types of social security recipients. It contains a particular focus on children and families. We find financial stress has declined through recent decades across the whole population. However, those receiving working age social security payments such as the disability support pension, Carer Payment, Parenting Payment and JobSeeker have been left behind. Their financial stress and poverty levels have worsened through Australia's long economic boom of the last 30 years.

The current planned rate of income support will leave 789,000 children in Australia living in poverty (more than 1 in 6 children). Using the relationship between financial stress and income we estimate where additional funding for social security would best be spent and what impact such spending could have on financial stress and poverty in Australia. The report finds that increasing overall social security spending by up to 20 per cent yields strong benefits in terms of reducing poverty and financial stress when targeted towards working age payments with high rates of poverty and financial stress. These include JobSeeker Payment, Parenting Payment Single, Disability Support Pension and Carer Payment.

Keywords: *Social security, financial stress, microsimulation, optimal policy modelling*

Capturing the widespread ripple effects of familial intellectual disability and potential benefits of genomics

Deborah Schofield[a], Owen Tan[a], Rupendra Shrestha[a], Sarah West[a], Jackie Boyle[b], Louise Christie[b], Melanie Leffler[b], Natalie Hart[a], Katherine Lim[a], Robert Tanton[c], Jinjing Li[c], Tony Roscioli[d] and Mike Field[b]

[a] GenIMPACT, Centre for Economic Impacts of Genomic Medicine, Macquarie University
[b] Genetics of Learning Disability Service (GoLD), NSW Health
[c] University of Canberra
[d] Sydney Childrens Hospital
Email: deborah.schofield@mq.edu.au

Abstract: Determining the cost effectiveness of genomic medicine has been limited by available data. Many studies have focused on the cost of genomic sequencing with cost effectiveness often assessed on the basis of the cost per additional diagnosis. However, due to the relatively recent capacity to provide a molecular diagnosis for many conditions, and lack of direct access to clinical cohorts, many studies have been unable to take account of the impact of health outcomes using standard measures such as QALYs. This is a particular limitation when studies are required to support access to public funding as there is no recognised threshold for funding of a diagnosis alone. Further, genetic information is often of benefit to other family members, including to inform reproductive planning where there is a risk of recurrence of the condition. Due to the highly disabling and life-long nature of many genetic conditions, the costs beyond the health system are also often large, suggesting the importance of taking a societal perspective. In this session, we demonstrate how we are addressing these issues in several ground-breaking studies on the benefits and cost effectiveness of genomic medicine.

We report on the first large, in-depth study exploring the economic, psychosocial and potential reproductive impacts of a molecular diagnosis for moderate to severe intellectual disability (ID) in the EPIC-ID study. To date, we have surveyed over 100 families from the Genetics of Learning Disability service and Liverpool Hospital, Sydney. A survey instrument was developed specifically for this study to assess quality of life and a range of psychosocial factors, income, welfare, savings and assets, education and employment, living arrangements, transport and other subsidies and family out-of-pocket costs. From our preliminary data, we estimated lifetime costs to government and private households totalling about $10 million per household. The cost burden on families is high, mainly due to lost income and out-of-pocket expenses. Government incurs substantial costs for health services as well as for special education and supported accommodation. The families are also under significant psychosocial strain, with the majority of carers reporting levels of depression, anxiety, and stress indicative of a need for clinical intervention. Our study shows that families affected by ID experience significant burden. This data will be used to benchmark the potential benefits of precision medicine and informed reproductive decision making in a large-scale microsimulation model.

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Keywords: *Intellectual disability, genomics, microsimulation model*

Cost effectiveness of genomic medicine for mitochondrial diseases

Rupendra Shrestha[a], **Deborah Schofield**[a], **Sameen Haque**[b], **Owen Tan**[a], **Katherine Lim**[a], **Karen Crawley**[b] **and Carolyn Sue**[b]

[a] *Centre for Economic Impacts of Genomic Medicine (GenIMPACT), Macquarie University,*
[b] *The Kolling Institute, Royal North Shore Hospital*
Email: rupendra.shrestha@mq.edu.au

Abstract: Mitochondrial diseases (MDs) are one of the most common forms of inherited neurological disorders caused by genetic mutations in either mitochondrial DNA or nuclear DNA. Some patients with mitochondrial diseases may present with a single symptom while others may have several different clinical presentations involving multiple systems such as muscle weakness, diabetes, heart failure or visual loss. MD is often challenging to diagnose given its varied clinical presentation and genetic heterogeneity. With the emerging field of genomics and the next generation sequencing, the genetic diagnoses of MDs have been gradually improving and taking less time to diagnose. Early and precise genetic diagnosis of MDs would enable early intervention and the affected patients can be managed with personalised gene-specific treatment.

Evidence of cost effectiveness are required to support access to public funding for next generation sequencing and the personalised medicine for patients affected by mitochondrial diseases. In this presentation, we describe a cost-effectiveness model of using next generation sequencing for genetic diagnoses of MDs and the potential personalised treatment as a result of genetic diagnoses compared to the current standard diagnostic approach using muscle biopsy.

We developed a cost effectiveness model based on a cohort of patients with mitochondrial diseases recruited from the Mitochondrial Disease Clinic at the Kolling Institute, Royal North Shore Hospital. We collected information on their clinical presentation, their diagnoses using the next generation sequencing and the standard diagnostic approach, the clinical management of their mitochondrial diseases from clinical records and their health related quality of life and the utility using a standardised quality of life instrument AQoL-8D (Assessment of Quality of Life). We sourced costs which included the costs of diagnostic pathways and the costs of personalised treatment, if any, as a result of genetic diagnoses from the published data. Health outcomes and the utility for their health status with personalised treatment and in absence of personalised treatment for those with genetic diagnosis were simulated.

Using our cost-effectiveness model, we will simulate incremental cost per additional diagnosis of using next generation sequencing compared to standard diagnostic pathway and incremental cost per quality adjusted life years gained from the use of personalised treatment. The results will provide much needed evidence for publicly funded next generation sequencing for the diagnosis of mitochondrial diseases.

Keywords: *Mitochondrial disease, genomics, precision medicine, cost-effectiveness*

Cost effectiveness analysis of precision medicine in childhood cancer

Owen Tan[a], **Deborah Schofield**[a] **and Rupendra Shrestha**[a]

[a] *Centre for Economic Impacts of Genomic Medicine (GenIMPACT), Macquarie Business School, Macquarie University, Australia.*
Email: owen.tan@mq.edu.au

Abstract: Advanced in genomic sequencing technology enabled the in-depth understanding of cancer driving mutations at in cancer patients, which led to potential application of genomic-guided precision medicine. The aims of this study was to the cost and benefit of applying the next generation sequencing (NGS) in the management of childhood cancer through a novel microsimulation model, Paediatric Cancer MOD (PeCanMOD).

Records of patients' under the age of 18 years in New South Wales (NSW), Australia were extracted from the NSW Central Cancer Registry and were linked to mortality and hospital datasets. We simulated the distribution of genomic mutations of these patients using information obtained from 1,200 molecularly profiled paediatric cancer from the Foundation Medicine Pediatric Portal (Chmielecki et al., 2017). Imputation of having specific genomic variants was carried out based on the distribution of genomic variants in each cancer type (55 categories) and allocated using Monte Carlo simulation methods by cancer type. The simulation process was repeated 1,000 times. The model simulated the number of individuals eligible for precision medicine, and incremental cost of treatment per quality-adjusted life year (QALY) and life year (LY) gained if precision medicine were introduced to late stage cancer patients as the last treatment option. The model assigned a multiplier to individuals to reflect the number of childhood cancer patients with similar characteristics within the Australian population based on the data published by the Australian Institute of Health and Welfare (AIHW) (Australian Institute of Health and Welfare, 2019). The analysis was conducted in SAS and Excel.

The total costs of the precision medicine program, including costs of sequencing, and costs of treatments was AU$367,589 per year and annual average costs per individual was AU$12,253. About 19% of individuals would be eligible for precision medicine treatment. The overall incremental cost per QALY gained was AU$337,155 (CI: AU$106,061-1,548,216). The modelled incremental cost per QALY gained was sensitive to effectiveness of precision medicine and costs of sequencing. A cost-effective outcome could be achieved with a higher proportion of patients treated with precision medicine, combined with lower drug and sequencing costs and improved survival outcome.

We have demonstrated the feasibility of using microsimulation modelling to simulate cost-effectiveness of precision medicine in childhood cancer care. The model suggested that this simulated precision medicine program is unlikely to be cost-effective at this current setup.

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Keywords: *Precision medicine, health data, paediatric cancers*

Simulating the impact of Australian Capital Territory Electric Vehicle policy

Y. Vidyattama [a], R. Tanton [a], D. Sinclair [b], J. Schirmer [b] and B. McCaffrie [b]

[a] *National Centre for Social and Economic Modelling, University of Canberra, Bruce, Australia, b Centre for Change Governance, University of Canberra, Bruce, Australia*
Email: yogi.vidyattama@canberra.edu.au

Abstract: The introduction of electric vehicles and their many variants is an important step in the effort to reduce greenhouse emissions and dependence on fossil fuels. Nevertheless, the take up rate of electric vehicles is still low. The Australian Capital Territory is one of the jurisdictions in Australia who has offered incentive for people to convert to the Electric Vehicle usage. This includes Stamp duty exemption; two years free registration and Interest free loan up to 15,000 Australian dollar.

This project aims to estimate the number of electric vehicles in the ACT in five years and in particularly, estimate the impact of ACT Zero emission Vehicle policy on the demand of electric vehicles. The research questions for this project are not only by how much the policy affects demand but also in which parts of Canberra community the demand affected.

The methodology for these estimations is spatial microsimulation model. This model is necessary since the spatial microsimulation modelling is intended to estimate the distributional impacts of potential policies designed to incentivise the uptake of EVs in the ACT, not only based on income but also on family type and residential location. This includes a Base Case of current/proposed EV policy settings, and three alternative scenarios based on the two years free registration and Interest free loan up to 15,000 Australian dollar offers. To do so, the model used the earlier vehicle modelling that distribute household and their vehicle based on SA2 or suburb location in ACT. The preference and total Cost of Ownership model will then be applied to model the decision of buying electric vehicle. Therefore, a survey to gauge the ACT community's knowledge and understanding of electric vehicle policy has been done to inform the model.

The results show the policy may increase the demand for electric vehicle although not as much as if the prices are lower. The policy will help the lower income household (especially the second lowest quintile) but the demand still dominated by the highest quintile. It may also help distribute the electric vehicle ownership to the south of Canberra.

Keywords: *Electric vehicle, spatial microsimulation, distributional impact, policy analysis*

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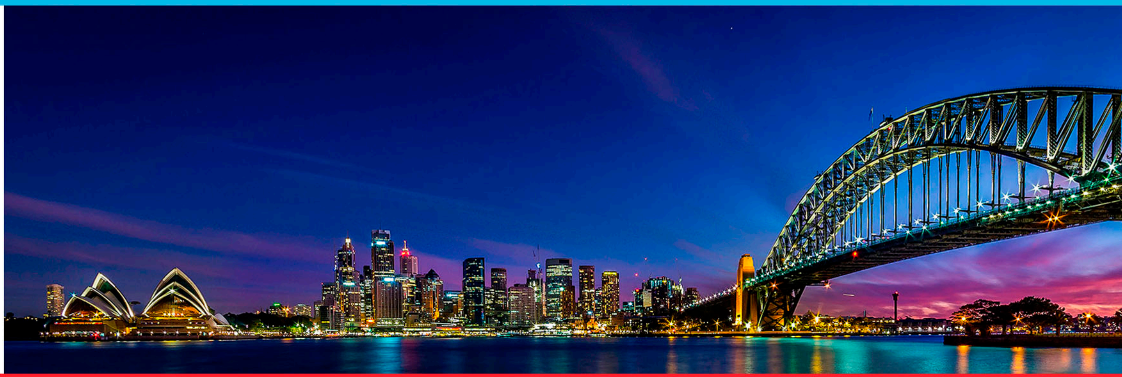

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