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Benefits and limitations of current approaches to whole of catchment modelling

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Abstract: Developments in catchment modelling frameworks, such as the new WaterCAST tool developed by the eWater CRC, have improved the ability to model catchment management and land use changes at the whole of catchment scale. While these tools have given modellers greater flexibility in the approaches, algorithms and frameworks which can be applied to a particular catchment, this paper will examine these improvements through a number of case studies and discuss current benefits and limitations when modelling with the WaterCAST tool at this scale.

In the application of catchment models, significant effort is focused on the prediction and calibration of hydrology, however we still have considerable limitations in terms of understanding and predicting hydrologic change through the application of catchment management activities, both in urban and rural land uses. Even at the fundamental level, our ability to discretise between different hydrologic responses driven by spatial characteristics (e.g. different vegetation types, soil characteristics, land management practices, slope etc) is still limited, due to both a lack of process understanding and the difficulty in obtaining sufficient data and at appropriate resolutions.

While hydrologic modelling has seen considerable research effort, advances in the modelling of water quality have not progressed by a similar amount, and once again, data limitations may be the key cause of this. Furthermore, advances in the understanding of water quality constituent generation, transport and delivery are still mostly treated at a coarse level such as event mean concentration approaches, and while some advances have been made in understanding water quality processes, the majority of these have yet to be transferred to the whole of catchment modelling frameworks.

The current state of catchment modelling in Australia with respect to application of the WaterCAST tool is discussed within this paper, focusing on hydrology, water quality, scale issues (both temporal and spatial), conceptual modelling approaches and data limitations. This shows that the application of the WaterCAST framework provides a flexible modelling platform, however further developments are required to exploit its full potential. This paper also presents a number of case studies highlighting the 'state of play' with modelling the whole of catchment scale and discusses what is required in order to improve out predictive capabilities in terms of the impacts of catchment management and catchment change.

Keywords: *catchment modelling, WaterCAST, hydrologic parameterisation, water quality modelling*

1. INTRODUCTION

Catchment modelling in Australia has developed considerably in recent years, through the efforts of government agencies, academia, research groups, consultancies and dedicated forums such as MODSIM. While the number of catchment models at the broad scale (>100 km^2) has increased, and the number of catchment modellers has also risen (based on over 2,000 downloads of the E2 and WaterCAST catchment modelling software via the eWater CRC toolkit), this paper examines whether, with this increased modelling effort and new software frameworks, the status of catchment modelling has significantly improved in the last decade. To support this discussion, four case studies of the latest applications of the WaterCAST framework are presented, highlighting both the benefits and limitations of current approaches.

2. CATCHMENT MODELLING USING WATERCAST

2.1. Background

At the beginning of this decade, a new catchment modelling tool, EMSS (Environmental Management Support System) was released (Vertessy et al, 2001). This software, based on the Tarsier modelling framework (Watson et al, 2001) allowed a comprehensive, spatially based model of catchments to be developed. Originally applied in South East Queensland, further development of the modelling framework through the CRC for Catchment Hydrology's Development Projects (Young et al, 2003) saw the software applied extensively across Australia. These applications highlighted limitations in the EMSS when adapting the software to a wide range of catchment conditions, as all major component models were hard wired and could only be parameterised to attempt to account for these variations. In recognising this, the CRC embarked on further development of catchment modelling frameworks (Rahman et al, 2005), leading to the development of the E2 modelling tool. This tool allowed a greater degree of flexibility in the choice of component models, units, spatial data, temporal data and model outputs, and the ability to write and import new models using the code written in languages compatible with the Microsoft dot net framework.

From the E2 software, further developments in the component models and structures were made within the new eWater CRC resulting in the development of the WaterCAST tool. This tool, the successor to E2, is a significantly updated version of the former tool, but based on the same core structure, with flexible component models, the ability to write new models and more flexible model interrogation and reporting. Fundamentally however, the modelling approach is the same as applied in EMSS, rainfall-runoff modelling, constituent generation, stream routing, filtering and delivery to outlets.

Catchment model construction within WaterCAST requires the user to define which model components are required and how they should be linked together. The underlying data within the model is a spatial description of the catchment, whether simply a subcatchment map or one derived from a digital elevation model. These subcatchments are either manually or automatically joined together via a node-link network that describes the hydrologic connectivity of the system being modelled. This is then parameterised and calibrated to complete the catchment model.

In developing WaterCAST catchment models throughout Australia, the authors have worked through the above process on numerous modelling applications and have therefore been required to consider the advantages and limitations of the tool in each of these. Key considerations in the development of the models are discussed below and in the following case studies.

2.2. Lumped Conceptual vs Process Based Approaches

The WaterCAST framework is currently aligned towards lumped, conceptual style modelling processes. This is consistent with the previous E2 and EMSS approaches, however it is not limited to this as additional process descriptive algorithms can be written and added by the user. While the lumped conceptual approach has been found to be suitable in predicting relative subcatchment loads, considerable discrepancies have arisen when process and lumped conceptual models have been developed in the same catchments, with sometimes order of magnitude differences (Ellis et al, 2005). Commonly, process based models such as SedNet (Wilkinson et al, 2004) replicate fine scale processes and accumulate these to a whole of basin scale whereas lumped conceptual models tend to describe broad scale catchment responses and relate these back to finer scale spatial characteristics (e.g. land use).

The lumped conceptual approach is well suited to spatial data sets commonly held by government agencies, such as land use, cadastral boundaries and drainage information, whereas process based models can require specialised data collection activities to describe particular process parameters (e.g. gully density, soil mapping etc). The disadvantage of the lumped conceptual approach is that it is usually difficult or undesirable to relate spatially or temporally variable parameters to the “lumps” (such as land use) as there is usually a desire to reduce model complexity wherever possible. The inherent variability in the data is then usually lost in this technique as a particular “lump” is described in a similar fashion regardless of its spatial or temporal variability (e.g. all grazing lands are treated equally, even though stocking rates may differ considerably).

2.3. Scale – Spatial and Temporal

Current applications of WaterCAST are usually constructed around a 10 to 50 year climatic period running on a daily time step. While usually more than sufficient where mean annual load predictions are required, daily time steps may limit accurate prediction of flow routing and constituent transformation processes which often work at sub-daily scales such as in urban environments.

Spatial scale within catchment models is always a trade off between the size of the catchment being studied, the data resolution and model complexity in terms of file size and model run time. There is a tendency to use the finest resolution data available, and while sometimes desirable, often more coarse data resolutions may be far more appropriate to the scale of question being asked. No firm rules of thumb have been developed, however rarely would data with a cell size of <10m be used. Typically, where mean annual loads at the whole of catchment scale, fine resolution spatial data is not usually required or is beyond the inherent resolution in the modelling process or algorithm. For example, event mean concentrations are usually derived from data collected downstream of relatively homogeneous land uses in the order of 100ha or greater. It is therefore not considered appropriate to apply these concentrations to land uses mapped to 5m cells as this is well below the inherent resolution of the model parameter.

In the application of the WaterCAST framework, we have found that it is always best to consider the number of subcatchments in developing the model, and this then becomes the key driver in data resolution. In most models, the number of subcatchments derived is typically around 80-160. The size of the each subcatchment varies within the model and is usually dictated by a predefined subcatchment map prepared in a GIS. These are manipulated to give a reasonable number of subcatchments. Once this is completed, the data resolution can be refined so as to be appropriate for the subcatchment size.

2.4. Spatial Characteristics

Current applications of catchment models typically represent a point in time, with static data for most spatial characteristics such as slope, soils, vegetative cover and land use. Obviously, some of these are unlikely to experience dynamic change in the period being modelled, however vegetative cover and land use typically change within the climatic period being modelled and for cover, seasonal change may be quite critical if catchment flows and loads are to be accurately represented. Some models, such as GRASP (Littleboy and Mckeen in Dalal-Clayton and Dent, 2001), have the ability to simulate this, but while this aspect may be well represented within models such as these, it is not available within a more complex catchment modelling framework such as WaterCAST.

2.5. Hydrology

The ability to model and calibrate hydrologic processes within current catchment tools has improved significantly and further efforts are being directed towards this with the development of more complex combined hydrologic and water management models. While these advances have been useful, some fundamental hydrologic modelling issues are still present.

Firstly, as most models run on a daily time step, sub-daily hydrologic processes such as flow routing, cannot be adequately simulated. Previous catchment models such as EMSS could do this by disaggregating flow to sub-daily time steps for routing calculations, but the WaterCAST framework does not yet allow this. However, sub-daily modelling is possible by inputting hourly data as a longer simulation period with a pseudo-daily time step (e.g. 1 day of hourly data becomes 24 days of pseudo-daily time step input data).

Secondly, rainfall data used as inputs into hydrologic models are typically derived from national gridded data sets such as SILO (DNRW 2009). While this is useful, other rainfall data products are available (such as radar rainfall) which may represent both spatial and temporal rainfall variability in much greater detail. The impact of using such data has not yet been estimated in the catchment modelling arena, but it is anticipated that in tropical and sub-tropical environments, rainfall spatial and temporal heterogeneity may be significant factors.

2.6. Water Quality

By far the area of catchment modelling which has not yet seen significant development is the modelling of water quality processes. In the vast majority of catchment modelling applications, a simple event mean concentration/dry weather concentration (EMC/DWC) approach has been utilised, with the implied understanding that this method yields results which do not calibrate well with observed data. However, this approach can be appropriate for both estimating long term loads and being able to attribute land use effects with constituent load generation.

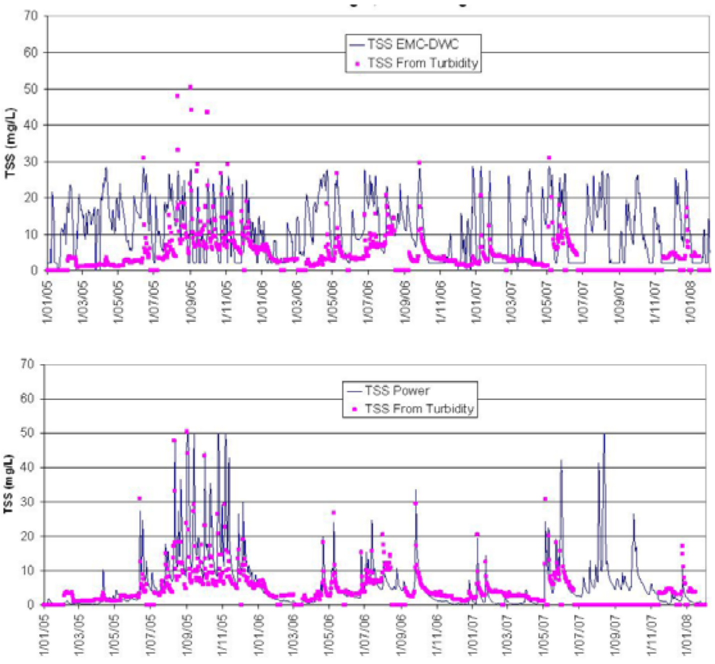

Figure 1. Constituent Generation using EMC/DWC and Flow Based Power Function Relationships.

Recent applications of flow based constituent generation models have shown considerable promise and with some refinement, may allow a much better representation of the dynamics of catchment scale constituent generation. This is exemplified by the Figure 1 which outlines recent calibration studies for water quality data undertaken in North East Tasmania using the EMC/DWC approach and a flow based power function. This is only one example of the type of improvement possible in constituent generation modelling.

There are a number of other factors which have been encountered in the application of the WaterCAST framework, such as storage modelling, calibration methods, uncertainty derivations and linkage of models. Some of these aspects are raised within the case studies below, and each would be worthy of a dedicated paper. Given this, we have not discussed these further but focused on the key issues discussed above.

3. CASE STUDIES

3.1. Botany Bay WSUD Retrofit Assessments

Botany Bay, located in Sydney, NSW is one of Australia's iconic waterways with significant historical, cultural, economic and ecological attributes. Recent water quality assessment in the Botany Bay region has focused on catchment management practices and their ultimate impacts on receiving environments (Weber 2008). This has been facilitated by coupling catchment models (including both MUSIC and E2/WaterCAST modelling frameworks) with receiving water quality and ecosystem health models (DYRESM-ELCOM).

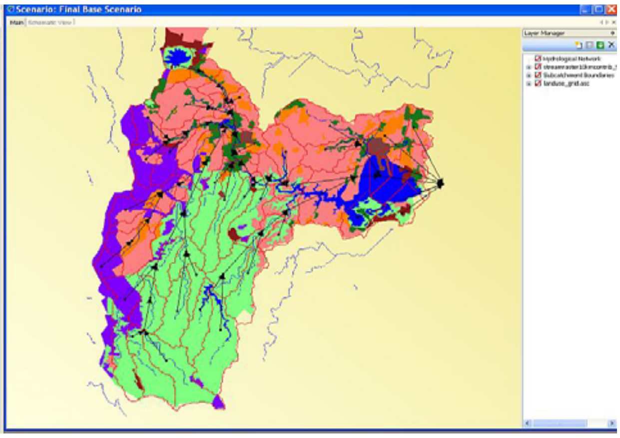

Figure 2. Botany Bay E2/WaterCAST model

A component of this project involved the assessment of the relative contributions of pollutants to the receiving environment from existing urban and greenfield development. This required the creation of both present and future land use maps for the Botany Bay region.

One of the outcomes of the application of the WaterCAST framework in this catchment was the assessment of urban best management practices, such as Water Sensitive Urban Design (WSUD), within the MUSIC

(Model for Urban Stormwater Improvement Conceptualisation, Fletcher et al ,2001.) modelling tool. The results of this assessment were incorporated within the WaterCAST tool, and results from the catchment model set as boundary conditions for the DYRESM-ELCOM model. This is one of the few “source to sea” modelling efforts attempting to quantify the impact of best management practices on ultimate receiving water quality.

The application of these models showed that the time step required for each model was considerably different, with MUSIC requiring 6 minute time steps, E2/WaterCAST requiring daily data, and DYRESM-ELCOM requiring hourly data. In hindsight, it would have been far better to model all components in at least hourly time steps, with sub-hourly perhaps being required within MUSIC, depending on the WSUD measure being simulated.

3.2. South Alligator River Climate Change Assessment

The South Alligator catchment model (11,700 km^2) was developed to facilitate a high level assessment of the potential impacts of sea level rise due to climate change on the environmental values of the South Alligator River region in the Northern Territory. A daily time step model was constructed in the WaterCAST framework to provide freshwater flows and sediment loads to a recently developed floodplain model (TUFLOW FV) which accounted for tidal inundation and sea level rise.

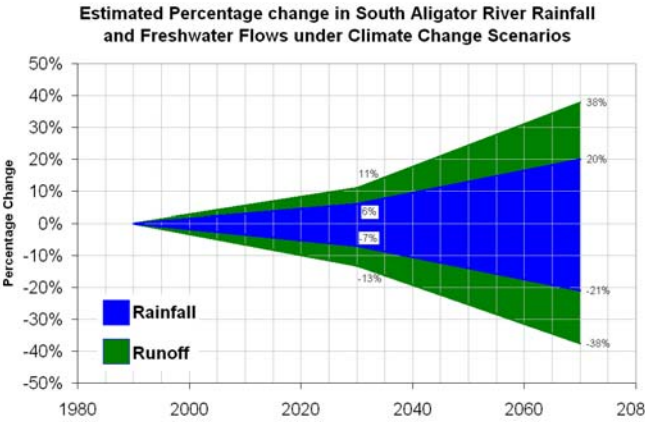

Figure 3. South Alligator River Climate Change Impacts on Stream Flows

Nine climate change model scenarios derived from predictions from the Intergovernmental Panel on Climate Change were generated reflecting potential changes to rainfall and potential evapotranspiration totals (percentages). Climate scaling was undertaken outside of the WaterCAST framework as the tools to do this over gridded data for the entire model domain are not yet available in WaterCAST.

Selected model results shown in Figure 3 highlight that scaling of rainfall has a disproportionate impact on the runoff volumes predicted by the model. The use of EMC/DWC constituent generation for this model resulted in similar increases/decreases in sediment and nutrient loads as those predicted for flows due to the simplistic representation of constituent generation. Constituent scaling or accounting for land cover variability under climate change was not implemented in the model due to high uncertainty and lack of inbuilt tools to facilitate this scaling.

3.3. Murraylands Instream Losses

Figure 4. Murraylands Model

The Murraylands E2/WaterCAST model (Figure 4) was developed to assist the South Australian EPA in understanding and managing pollutant inputs to the South Australian Murray-Darling Basin (SAMDB) (Mosley et al 2008). The model extends over an area of approximately 68,000 km^2 and incorporates the lands from the South Australian – Victorian Border to the Murray mouth. The key area of interest for the Murraylands E2/WaterCAST model was the Eastern Mt Lofty Ranges and catchments contributing Lake Alexandrina.

Hydrological parameterisation of the Eastern Mount Lofty Ranges (EMLR) catchments was undertaken using RRL (eWater CRC 2009) including the Bremer and Angas Rivers. These rivers have a number of gauges located in succession and analysis of flow data indicated that a loss of up to 50% of volume was occurring between upper and lower gauge sites, potentially impacting on the volume of flow to Lake Alexandrina. A spreadsheet tool was developed to describe this loss of flow and then ‘reverse engineered’ so that it could be implemented as an E2 storage in a ‘link’ in the Murraylands E2/WaterCAST Model.

The successful parameterisation of the instream loss model via an E2 storage could not have been efficiently undertaken if not formulated in a spreadsheet beforehand. The current WaterCAST framework has limited support for automatic manipulation and optimisation of storage parameters for model calibration, highlighting the current need to parameterise E2 storages independent of the WaterCAST framework before implementation in a catchment model.

3.4. Port Phillip and Western Port PEST Parameterisation

The Ports E2/WaterCAST model was constructed for Melbourne Water to facilitate the assessment of potential pollutant loads delivered to Port Phillip and Western Port region in Victoria. In the latest application for this region, WaterCAST models were constructed to assess actual loads rather than assess the relative differences between model scenarios, therefore incorporating vast amounts of data used for undertaking detailed parameterisation of up to 14 major drainage catchments.

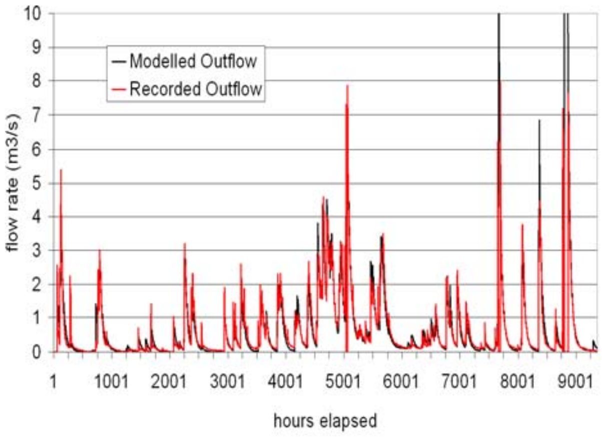

Figure 5. Hourly Model Calibration Results

Hydrological parameterisation of these 14 major catchments of the Ports E2/WaterCAST model was undertaken using PEST (Doherty 2007). Until recently, E2/WaterCAST did not have the functionality to operate with PEST. However, a command line version of WaterCAST was developed by QScape and the Queensland Department of Natural Resources and Water (Ellis, 2009) which was made available for this study. Seven of the major catchments were parameterised using AWBM on an hourly time step, while the remainder were parameterised using SIMHYD over a daily time step. Multiple time steps were required across the model domain to best reflect the catchment responses to rainfall as significant proportions of the catchment are urbanised. An example hourly time step calibration is shown in Figure 5.

Water quality parameterisation was undertaken outside of the WaterCAST framework due to limitations in process representation. Observed pollutant concentrations shows characteristics not suited to land use based EMC/DWC pollutant export modelling approaches.

Parameterisation undertaken for this project was also restricted by excessive data requirements of the numerous point sources, water extractions, storage operations and unaccounted for baseflows. Simulated low flows were particularly poor in terms of model fit with recorded streamflow data, showing the need to thoroughly upgrade all available time series when attempting to further upgrade the model.

The number of parameters that this project attempted to estimate relating to up to 16 land uses per catchment was too many highlighting the disparity between management needs for highly parameterised model domains and our actual ability to robustly parameterise such models. Therefore, despite this significant modelling effort, estimating actual land use specific pollutant load estimates are not yet possible for the Ports E2/WaterCAST model domain despite this being a key management need.

4. CONCLUSIONS

The application of the WaterCAST modelling framework in Australia has allowed the assessment of the state of catchment modelling components using this tool on projects within the country. It is obvious that while advances have been made in particular components, significant advances in modelling catchments for flow and constituents are yet to be thoroughly realised. The approaches discussed highlight that the WaterCAST framework is eminently flexible and offers a platform on which this development can be undertaken. The linkage of PEST and WaterCAST is a significant advancement and allows robust parameterisation of complex models, however water quality simulation tools currently available are too simplistic to allow calibration to collected data in the same way hydrologic data is used, both due to the available water quality models and the lack of continuous water quality data for particular constituent species (e.g. nitrogen).

Key areas for future development of the WaterCAST framework include more complex water quality constituent generation, time and spatial scale flexibility within the same model domain, land use/land cover change through time, inbuilt climate processors for climate change scenarios and more complex storage operations representation. These improvements to the WaterCAST modelling framework are necessary to allow increasing amounts of calibration data, better represent current conditions and keep pace with client needs for modelling complex and diverse future management scenarios.

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