Towards integrated modelling in the Murray-Darling Basin

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EXTENDED ABSTRACT

The Murray-Darling Basin is characterised by low but highly variable rainfall and surface runoff and a high level of surface water use. Regulation has altered the stream flow pattern dramatically, affecting river dependent ecosystems. Responsibility for land and water management is fragmented, producing varying (and sometimes disparate) policies, management, and modelling approaches. The Murray-Darling Basin Commission coordinates common strategies to cap further stream flow diversion, improve river ecology, and address stream salinity, nutrient pollution and algal blooms. Several risks to future water resources have been identified. Climate change and farm dam development are the most important, but others include reforestation, bushfire recovery, groundwater extraction, irrigation water management, and perhaps changed cropping patterns and a developing water trade market. The processes underlying these risks often interact, affect ecosystems and economies in different ways, and have implications for several strategies and policies. Therefore, a capacity for integrated assessment or a ‘systems approach’ is needed. In this paper, we describe the characteristics of the system we model, some of the questions we want to answer, issues encountered in developing an integrated modelling framework, and a roadmap for further development.

Achieving an integrated assessment capability requires an unprecedented level of model integration. We review past successes and failures in model development and application and extract a few guiding principles: keep the modelled system as simple as allowable; match the modelling approach to the time and space scales of the question being asked and the data available to drive the models; describe the processes at those scales, scaling up or down as required from the current scale of understanding if required; allow elementary process and statistical modules to be assembled ‘in time and space’ in a common, flexible modular framework; import existing models and develop new models within a common software platform; and increase collaboration, pooling of resources, and consistency between modelling approaches.

The CRC for Catchment Hydrology has made these aims achievable, by fostering collaboration and developing a model building platform and catchment modelling framework suitable for model integration.

We review the most important of the numerous individual models used in the Basin. They include climate models; catchment models (describing rainfall-runoff response and land use impact on stream flow, salinity, and sediment and nutrient loads); river operation and planning models; irrigation water use models; and groundwater models. The impact of stream flow changes on river dependent ecosystems, changes in water distribution through water trade, and the financial implications of land use change and salinity have also been modelled. Nearly all models have only been used for small parts of the Basin, the purpose of their use varies widely, and integration between models has been limited so far.

A staged and adaptive approach can be envisaged to effectively and efficiently increase our modelling capacity. In the short term, we can build on the technology that already exists, applying selected models across the entire Basin and integrating river models where possible. In the medium term (2-5 years), data collection and modelling should be consolidated, standardised and shared to achieve greater consistency across the basin. Critical science gaps that need to be addressed to progress in the longer term (5-10 years) include: data collection to test and improve stream flow quality models; larger-scale models of farm dam and bushfire impacts; models describing the interaction between stream flow, quality and ecology along the river; integrated water resource and economic models; and increasing our ability to predict the outcomes of social processes. These developments will require an unprecedented level of collaboration. Fortunately, institutional, research and technology developments seem to be aligning.

1. INTRODUCTION

Water resources in the Murray-Darling Basin are under increasing pressure to satisfy often conflicting objectives. Natural processes and changes in land use and river management have led to further degradation of water quality and ecosystem health. There is a need to find ways to increase the social, economic and environmental benefits derived from water use. This requires integration of models[1] to better describe our understanding of (parts of) this large and complex system. Different models can reflect different conceptualisations of the world, operate on disparate space and time scales, use different assumptions, and can interact, or should be able to. Integrating them in an efficient way is a daunting task and we have only just begun to address this. In this paper, we describe the characteristics of the system we seek to model, some of the questions we want to answer, issues encountered in developing an integrated modelling framework, and a roadmap for further development.

2. BASIN CHARACTERISTICS

The Murray-Darling Basin occupies 1.1 million km^2 (about 14% of the Australian continent) and contains more than 2 million people. It produces 20% of Australia's agricultural production and 60% of irrigated cropping. The main irrigation uses are flood irrigation of pasture and rice in the south of the Basin, and cotton in the north. The Murray River in particular is of great cultural, recreational and ecological significance and flows through several Ramsar-listed wetlands. Most of the Basin can be described as predominantly flat and dry, with relief and rainfall increases towards the south-eastern edges of the Basin. Annual rainfall increases from 200 mm along the western desert edge to more than 2000 mm in the alpine highlands. On average it is 480 mm, but highly variable. Total stream flow generated in the Basin accounts for only 5% of incoming rainfall. Most is generated in the uplands and a substantial part is intercepted in storage reservoirs. In the Murray River system, most of the stored water is released to irrigators further downstream during the dry summer months. This has effectively inversed the seasonal flow pattern in the southern rivers, and flow has also become less variable between years.

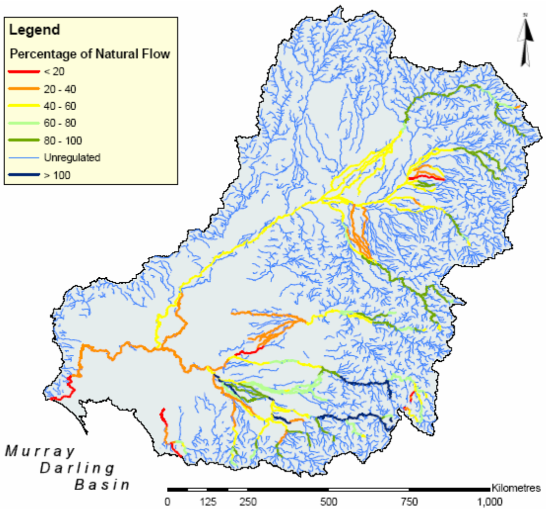

Figure 1. Murray-Darling Basin showing the river network and the difference between present and natural annual stream flow (Source: DeRose *et al.*, 2003).

About 11,000 GL of the 25,000 GL average annual stream flow are diverted, while another 11,000 GL is lost from the system, mainly by evapotranspiration from or near the river (M. Kirby, pres. comm., Figure 1). Under natural conditions 12,000 GL of stream flow is estimated to reach the sea, but this has reduced to around 3,000 GL at present (i.e. less than 1% of rainfall), and dry years such as 2002/3 when the river mouth was closed. In addition to surface water, more than 1,500 GL groundwater is extracted (mainly) for irrigation. In some cases, this groundwater has accumulated over a very long time and use is unsustainable. In other cases, the aquifers are connected to the river system and pumping affects stream flow. Land and water management in the Basin are the responsibility of 4 states and a territory and this has produced a complex policy and management environment and a diversity of modelling approaches to support this.

3. WHAT ARE THE ISSUES?

The amount of storage and high level of consumptive water use have led to a situation where surface water resources, in the Basin, have been almost fully allocated or over-allocated (i.e., the total of water entitlements cannot be met in all years). A cap on further stream flow diversions was introduced in 1997, and there is increasing water trade. Wetlands along the Murray River have gone into severe decline, which has been attributed to the reduction of high flows. The Living Murray Initiative includes a decision to reduce mean stream flow diversions by 500 GL

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[1] We define 'model' as equations describing a cause-effect relationship implemented in computer code, and 'model integration' as using quantitative outputs from one model as input to another.

(or 4.5%), to be used for ‘environmental flows’ to support ecological rehabilitation. Research is underway to evaluate how these flows can be recovered with the least amount of pain and supplied with maximum benefits. Salinity problems induced by land clearing and irrigation drainage are of ongoing concern. The MDBC has a strategy in place to reduce salinity through a combination of pumping and saline groundwater disposal at key locations along the lower Murray River, and bringing back deeper rooted vegetation in contributing catchments. Sediment and nutrient pollution associated with land and fertilizer use, and their effect on river ecosystems and toxic algal blooms, are also of concern. Finally, there are a number of factors that can threaten future water resources. Uncontrollable risks are climate variability and change, and recovery from the extensive 2003 bushfires (which may change catchment water yields for decades). Controllable risks include increases in farm dams and afforestation (both reduce water yield from upland catchments) and groundwater use (which can also reduce stream flow downstream). Increased efficiency in irrigation water management, changes in cropping patterns, and development of water markets, can equally present threats as solutions. Climate change and farm dam development are thought to be the greatest threat to surface water resources, but other risks can also cause significant reductions (Figure 2).

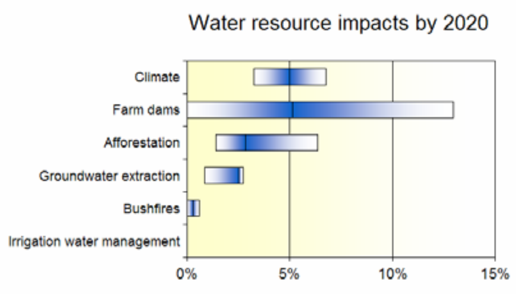

Figure 2. Estimated impact of six risks on Murray River flows by 2020, the darkest colour showing the most likely impact.

4. A NEW MODELLING PARADIGM

4.1. The need for a systems approach

The combined impact of the above risks on water security and river health is potentially dramatic, but simply adding them up is too simplistic. Reductions may be greater when water resources are scarce or abundant, or ecosystems may be more or less sensitive. Furthermore, the processes causing these risks can also affect the generation and delivery of salt and other stream pollutants. There are interactions between processes that can amplify or attenuate the combined impact. Only considering a part of the system in isolation can oversimplify our predictions even to the point of futility. An integrated assessment requires an unprecedented integration of different model components of this large, complex and interconnected system. Model integration is an essential requirement of a ‘systems approach’. However, we can conceptualise the system in infinite detail, but won’t necessarily be able to build a operational model of it. This is not just because of the sheer size of the task, but also because of the lack of quantitative or even qualitative understanding of linkages, and of data to test and support the use models. The ‘art’ of model integration is to keep it as simple as allowable, but not make it any simpler than is appropriate to the question being asked.

4.2. Models to fit the scale of information

Modelling efforts around water in the Basin typically aim to relate changes in climate, land use and/or water distribution, to the sustainability of water allocation, economic production and/or ecosystem health. The two sets are linked by changes in volume of water stored in a reference area (e.g. a groundwater body, a reservoir) or the flow of water and/or constituents at a point in the river network. The time and space scale at which the key processes are understood and can be described vary widely, and this is reflected in the range of models. Temporal scale has two components: the time step of the model (often chosen to match the scale of process understanding) and the time frame (matching the purpose of modelling). Typical time scales of important processes and purposes are illustrated in Figure 3 (cf. Skoien *et al*., 2003).

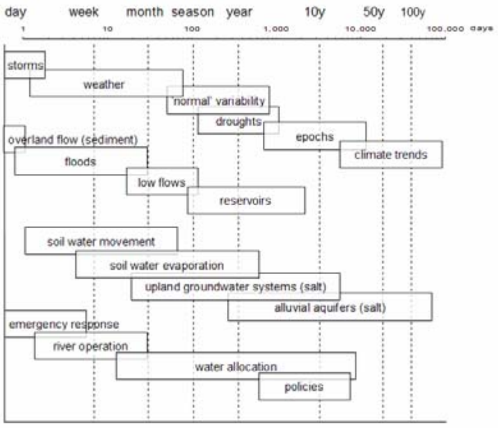

Figure 3. Typical time scales of different modelled processes and modelling purposes.

Shortening the time step or lengthening the time frame increases the data and effort required to use a model, without necessarily reducing uncertainty. In many cases there may be an opportunity to simplify very ‘large’ models by developing process models on longer time scales (e.g. by capturing emergent system behaviour). Equally, when models have much shorter time frames than the processes they simulate, there may be simpler approaches. Similar arguments can be made for the spatial aspects of modelling, i.e. granularity (or resolution, detail, or unit size) and coverage. The required granularity in climate and terrain input data and scenarios is often an important issue in this regard. In summary, the appropriate modelling scale appears to be determined by (1) the purpose, (2) the scales at which processes can be understood and described, and (3) the data available to drive models.

4.4. Horses for courses instead of Supermodels

Our present models have typically been developed by individuals or small teams. Often they started out small and simple, and addressed a rather narrowly defined question. Equally often, these models have ‘snowballed’ over time into large and complex models, driven by a broadening range of questions. Maintaining, servicing and even understanding such models becomes increasingly difficult and expensive. The questions being asked today are very diverse and as such one big model of all phenomena or ‘Supermodel’ is neither practical nor appropriate. A more flexible modelling approach is needed, and may be achieved by unravelling existing models to their fundamental units; (sets of) process equations developed in isolation. The equations selected for any given model should arguably be those that are closest to the original scale and scope of the research that led to them. Developments such as E2 (Argent *et al.*, this volume) provide such a flexible framework that allows modular components to be assembled. These components do not have to be limited to models, but can also be statistical prediction methods, scaling methods, etc. Both simple and more complex models can be built within the same framework. Inevitably, the greater flexibility of such frameworks also requires greater awareness and understanding on the part of the modeller about the constraints and appropriate use of the component modules.

4.5. Towards ‘Universal Plug and Play’ models

Model integration can occur in several ways, varying from manually passing numbers to automated two-way data passing in model run-time. User-friendliness increases rapidly in this order, but so do the initial energy, time and money spent on software engineering. Fully automated links are worthwhile developing if the effort required is saved on data transfer in subsequent applications. The CRC for Catchment Hydrology has invested much in a modelling platform that makes data passing between models easier and less model-specific (The Invisible Modelling Environment; Rahman *et al*., 2001). It makes integration much easier, allows different code languages, and negates the overheads of input-output data handling and visualisation. Efficient use of this platform puts requirements on the model code but not on input-output and visualisation. The investment in importing existing model code has proven worthwhile in several cases, and it provides a powerful platform for new model development.

4.6. Modeller Integration

Modular frameworks can also increase collaboration between people involved in module development. Framework sharing among different organisations creates an impetus for collaboration on its own, as the CRC for Catchment Hydrology has demonstrated. Its successor CRC eWater has 42 partners covering many of Australia’s natural resource management agencies. The pooling of resources allows them to meet their needs more efficiently. It also helps integrate modelling approaches in different agencies.

5. PRESENT MODELLING CAPACITY

5.1. Introduction

A wide range of models are already in use across the Basin to predict the impacts of changes in climate, land use, water use and river management. One way of categorising models and the linkages is shown in Figure 4. The capabilities and knowledge gaps in these groups are discussed below.

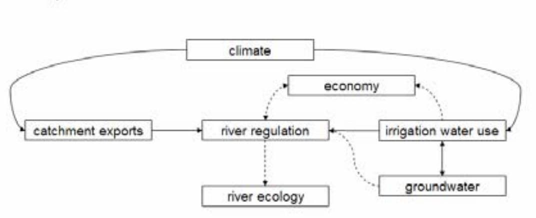

Figure 4. Types of models and the most common ways of integration so far (solid lines) and urgently required (dashed lines).

5.2. Climate models and methods

Historic climate records are still predominantly used for basin wide modelling. This has largely been due to the limitations of generating multiple replicates of rainfall on a daily basis across basins. Model capacity is now at a stage that a more probabilistic approach to modelling can be undertaken. Impacts of both climate variability and change can be considered. The Stochastic Climate Library (CMT, 2005) allows the stochastic generation of climate time series. A few studies have used climate sequences generated by statistical downscaling of climate model results, to feed into river models and predict water resources impacts (e.g. Viney et al., submitted).

5.3. Catchment models

Lumped rainfall-runoff models have been parameterised and calibrated for large proportion of the Basin. The Sacramento model (Burnash *et al.*, 1973) covers most of the NSW and Queensland uplands, whereas in Victoria and for the Murray River observed data is mostly used. The impact of afforestation on long-term water yield is commonly predicted using the curves published by Zhang *et al.* (2001). The recently developed Forest Cover Flow Change model extends this by allowing daily flow patterns to be adjusted for forest cover change (CMT, 2005). Distributed models have been developed to predict the water yield impacts of bushfires (Macaque; Peel *et al.*, 2002) and farm dams (TEDI; Neal *et al.*, 2002) and both have been applied in Victoria.

The coverage of water quality modelling across the Basin is sparser. Salinity is modelled most widely. Approaches vary considerably between jurisdictions, including distributed models such as CATSALT in NSW (Tuteja *et al.*, 2002), and the large-scale model BC2C (Dawes *et al.*, 2004) for assessment of upland catchments across the Basin. The semi-distributed 2Csalt model (Stenson *et al.*, 2005) is emerging as a model that may be applied across the Basin uplands. Longer-term sediment and nutrient budgets have been established for the entire Basin using the SedNet-ANNEX model (CMT, 2005), but vary in spatial detail and level of calibration. The E2 modelling framework (CMT, 2005) has modules for predicting the generation, delivery and transport of constituents. It is presently being applied to predict the impact of land use change on nutrient exports across Victoria.

5.4. River operation and planning models

Unlike catchment models, river models account for the impact of regulation structures and diversions on river flows. The distinction between approaches for operational (more or less immediate) and planning (longer-term) purposes is gradually disappearing. The ‘Big Three’ river models used in the Basin are IQQM in NSW and Queensland (Simons *et al.*, 1996), REALM in Victoria (Diment, 1999), and MSM-BIGMOD used by the MDBC for managing the Murray River (MDBC, 2001). All three models are embedded in legislation. The way that these models are used and the specific structure varies: IQQM operates on a daily or sub-daily basis, whereas REALM does not include routing. This has implications, for example for their use in assessing ecosystem response. Both models have been used to investigate water trade.

5.5. Irrigation water use models

Several models have been used to help increase the efficiency of irrigation water use, based on one-dimensional vegetation water balance models (Inman-Bamber, 2005). Irrigation water balance modules are also included with a considerable degree of process detail in IQQM, and in a regression based manner in MSM-BIGMOD.

5.6. Groundwater models

The predominant groundwater model used throughout the basin is MODFLOW (Harbaugh *et al.*, 2000). This model is implemented for a limited number of aquifers of interest across the Basin, in particular to evaluate sustainable groundwater yields in and near irrigation areas. Groundwater models have also been developed to assess the combined impact of land use change and salt interception schemes in the Lower Murray. The distribution of modelled groundwater systems across the Basin is fragmented, however, and interactions between groundwater and river are not accounted for.

5.7. Ecological models

The ecological outcomes of changes in stream flow and quality have been assessed to some extent by RAP (CMT, 2005) and MFAT (MDBC, 2005) to support River Murray ecological strategies. Floodplain models have been used to predict inundation of important wetlands along the Lower Murray at preset river stages, but cannot yet link river models to ecological models.

5.8. Socio-economic models

Our ability for integrated, large-scale economic and social analysis is very limited, but methods for partial analysis are available. Many, to a greater or lesser degree ‘ad-hoc’ economical analyses have been performed on water yield and salinity change predictions. For example, a temporary water trade model (WRAM; CMT, 2005) has been developed to support interbasin and interstate water trade studies. Much more model development is required in this area.

6. TOWARDS INTEGRATED MODELLING

6.1. Introduction

A staged and adaptive approach can be envisaged to effectively and efficiently increase our modelling capacity. In the short term (1-2 years), the best strategy arguably will be to build on the technology that already exists and add value. In the medium term (2-5 years), the data and modelling approaches can be consolidated and standardised to achieve greater consistency across the basin. In the longer term (5-10 years), a greater understanding of essential parts of the system will be required to make further progress.

6.2. Short-term: integration of existing models

Several catchment models have already applied to relatively large parts of the Basin. These allow us to make predictions of water and pollutant load changes in response to climate and land use change. Methods exist to disaggregate these typically long-term predictions to time scales that can be used in river models. Water quality models like 2CSalt, SedNet-ANNEX and E2 constituent modules can be applied across the Basin (in particular in the uplands) to allow accounting of salt, sediment and nutrients and so support the Murray River water quality strategies. Existing groundwater and surface water models will need to be integrated to avoid double counting of water resources and therefore unsustainable water use. This also implies expanding the present coverage of groundwater models. To assess how changes in catchment stream flow and groundwater interactions impact further down the river system, the ‘Big Three’ river models will need to be linked. In the short term this may continue as manual data transfers.

6.2. Medium-term: data access and collection and standardisation

All models rely on data for input and calibration. Data is currently scattered across agencies in a range of formats, and this is one of the major impediments towards model integration. Saving real-time data and accessing historic data through a ‘one stop shop’ should have priority. Current and future models should be built to integrate with this system. In the medium term, arguably a unified and consistent approach is also needed for river operations modelling across the Basin.

5.3. Long-term: lacking science and data

There are several models of stream flow quality (salinity, sediment and nutrients) but they lack in validation, and supporting data need to be collected at more stations. At present, our ability to predict the impacts of farm dams and bushfires is through distributed models that are hard to parameterise, and work is needed to develop simpler approaches to predict these impacts. Our understanding of the link between stream flow and quality on one hand, and river ecological response on the other, is deficient. This is an area where rapid development is needed. It requires scaling up existing ecological models and assessment methods, and collecting data along the river network. Floodplain models need to be better suited to the specific requirements of modelling inundation over large, dry and forested floodplains and, importantly, be linked to ecosystem health. Finally, the links between hydrological models and economic models are still weak, and social science is all but absent in our present modelling capacity. If our purpose is to increase the environmental, economical and social benefits of water use, then linking physical changes to these benefits should have high research priority.

6. CONCLUSIONS

Natural resource modelling in Australia is traditionally strong in large scale land use and water management planning. There is an increasing need to broaden our scope beyond this, to water resource sharing and quantifying the ecological and socio-economic implications of changes in hydrology in an integrated, systems approach. This requires an unprecedented level of collaboration, but the tide is with us. Government and agencies support collaborative approaches. The CRC eWater provides ongoing and new opportunities for researchers to jointly find innovative solutions to the challenges we face in natural resource management. Advances in sensor and ITC technology and a forward-thinking modelling community allow this to happen. The future looks bright.

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