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An integrated modelling framework for regulated river systems☆

Wendy D. Welsh[a,g,*], Jai Vaze[a,g], Dushmanta Dutta[a,g], David Rassam[b,g], Joel M. Rahman[c,g], Ian D. Jolly[d,g], Peter Wallbrink[a,g], Geoffrey M. Podger[a,g], Matthew Bethune[e,g], Matthew J. Hardy[f,g], Jin Teng[a,g], Julien Lerat[a,g]

[a] CSIRO Land and Water, GPO Box 1666, Canberra, ACT 2601, Australia
[b] CSIRO Land and Water, PO Box 2583, Brisbane, QLD 4001, Australia
[c] Flow Matters Pty Ltd, PO Box 272, Jamison Centre, ACT 2614, Australia
[d] CSIRO Land and Water, Private Mail Bag 2, Glen Osmond, SA 5064, Australia
[e] Murray-Darling Basin Authority, GPO Box 1801, Canberra, ACT 2601, Australia
[f] BMT WBM Pty Ltd, Level 5, 99 King Street, Melbourne, VIC 3000, Australia
[g] eWater Cooperative Research Centre, Innovation Centre Building 22, University Drive South, Bruce ACT 2617, Australia

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A B S T R A C T

Management of regulated water systems has become increasingly complex due to rapid socio-economic growth and environmental changes in river basins over recent decades. This paper introduces the Source Integrated Modelling System (IMS), and describes the individual modelling components and how they are integrated within it. It also describes the methods employed for tracking and assessment of uncertainties, as well as presenting outcomes of two case study applications.

Traditionally, the mathematical tools for water resources planning and management were generally designed for sectoral applications with, for example, groundwater being modelled separately from surface water. With the increasing complexity of water resources management in the 21st century those tools are becoming outmoded. Water management organisations are increasingly looking for new generation tools that allow integration across domains to assist their decision making processes for short-term operations and long-term planning; not only to meet current needs, but those of the future as well.

In response to the need for an integrated tool in the water industry in Australia, the eWater Cooperative Research Centre (CRC) has developed a new generation software package called the Source IMS. The Source IMS is an integrated modelling environment containing algorithms and approaches that allow defensible predictions of water flow and constituents from catchment sources to river outlets at the sea. It is designed and developed to provide a transparent, robust and repeatable approach to underpin a wide range of water planning and management purposes. It can be used to develop water sharing plans and underpin daily river operations, as well as be used for assessments on water quantity and quality due to changes in: i) land-use and climate; ii) demands (irrigation, urban, ecological); iii) infrastructure, such as weirs and reservoirs; iv) management rules that might be associated with these; and v) the impacts of all of the above on various ecological indices. The Source IMS integrates the existing knowledge and modelling capabilities used by different state and federal water agencies across Australia and has additional functionality required for the river system models that will underpin the next round of water sharing plans in the country. It is built in a flexible modelling environment to allow stakeholders to incorporate new scientific knowledge and modelling methods as they evolve, and is designed as a generic tool suitable for use across different jurisdictions. Due to its structure, the platform can be extended/customised for use in other countries and basins, particularly where there are boundary issues.

1. Introduction

Many of the large river systems around the world are highly regulated with numerous physical flow control and storage structures as well as a range of water sharing rules and regulations. By nature most regulated rivers are complicated socio-ecological systems that provide resources for a range of water needs: irrigation, urban use, and aquatic ecosystems such as wetlands. Water management organisations are facing increasingly complex challenges in management of water resources in these systems. This is due to a range of issues including: rapid growth in urban

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* Corresponding author. Tel.: +61 (0) 2 6246 5738.
E-mail address: wendy.welsh@csiro.au (W.D. Welsh).

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and agricultural sectors, environmental mandates, recreational interests, hydropower generation, over-allocation, changes to land-use, climate change, and the fragmented nature of available information. The challenges are even greater in transboundary river systems, where different parts of the basins fall under different political jurisdictions. In many cases complex legal rules have evolved over time as the level of resource development has increased, and with attempts to curtail water use upon identifying over-allocation. The water management challenges are compounded in the countries where temporal and spatial hydrological variability is very high. For example, in Australia, the driest inhabited continent on Earth, the fraction of rainfall that becomes runoff is smaller and the inter-annual variability of stream flow is higher than elsewhere in the world (Peel et al., 2004).

During the 1970s and 1980s, many site-specific river basin models were developed and used by engineers in water management organisations for operational planning of their basins (Zagona et al., 2001). Different organisations used different approaches and hardware and software technologies to develop the models suitable to their needs at that time. These models, with limited representation of hydrological processes, are not easily modified or flexible enough to apply in other sites and are unable to represent continually changing systems. For example, within the Murray-Darling Basin (MDB), which is the most important agricultural region in Australia and which produces one third of Australia's food supply, the MDB Authority (MDBA) and state water agencies responsible for management of water resources within the basin use different models (rainfall-runoff models and river system models) that are appropriate for their modelling needs. The New South Wales and Queensland state agencies use the daily Integrated Quantity and Quality Model (IQQM, Simons et al., 1996; Podger and Beecham, 2004; Podger, 2004; Vaze et al., 2011a) with the Sacramento rainfall-runoff model for most regions. The Victorian state agency uses the REALM model (Diment, 1991; Perera et al., 2005) at daily, weekly and monthly time steps. The Murray-Darling Basin Authority uses the Monthly Simulation Model (MSM, monthly) with BigMod (daily) (Close, 1996b; MDBC, 2002) to model river flow regulation in the Murray system. This makes combining individual models for the whole basin cumbersome, as downstream models require the outputs of upstream models as inputs, and these models are often run at different time steps (Welsh and Podger, 2008).

There are a number of general water management models with the ability to consider different hydrological processes such as MIKE SHE (DHI, 2011), TOPMODEL (Wolock, 1993), and HEC-HMS (Feldman, 2000), to model policy priorities such as HEC-5 SFCCS (USACE, 1998), WEAP (SEI, 2011) and HSPF (Bicknell et al., 1997), and to satisfy prioritised water rights in river basins such as MODSIM-DSS (CSU, 2011), WEAP (SEI, 2011) and WRAP (Wurbs, 2010). Although these tools have found many useful applications, their capabilities are not adequate to model both complex policies and water sharing rules (Zagona et al., 2001).

Another challenge faced by water management organisations is the lack of an integrated tool for both operational and planning purposes. Current operational tools model the river system in a manner that is distinctly different from the long-term planning tools used to develop water sharing plans. This creates a number of inconsistencies between the planning and operational management of river systems (Bridgart and Bethune, 2009). A review of the user requirements for a river operational tool undertaken by Nicholls (2006) shows that no existing operational tools in Australia meet the key user requirements, which are summarised in Bridgart and Bethune (2009). End users of these models have also expressed a strong desire for a tighter link between operational and planning tools, based on river management models (Nicholls, 2006).

The complexity and diversity of challenges faced by water management organisations highlight a continuing need for new advanced modelling tools to assist in decision making for operational and long-term planning to not only meet today's needs, but tomorrow's as well. Such a software tool requires an interdisciplinary framework to address multiple complex issues and should be able to mathematically represent key aspects of hydrological processes, flow control and storage infrastructure and management rules that occur within river basins, allowing users to investigate the combined effects of multiple influences such as changes in policy, operation, climate and land-use. Such tools need to be repeatable, transparent and defendable, especially as it is not uncommon for water allocations based on modelling to be contested in courts of law.

In recent years, with advancements in hardware and software technologies, several organisations in different countries have undertaken initiatives to develop new generation river systems modelling tools (Wurbs, 2005; Assaf et al., 2008) such as HEC-ResSim (USACE, 2010), MIKE BASIN (DHI, 2003), RIBASIM (Deltares, 2010), Decision Support Framework (DSF) (MRC, 2004), and RiverWare (Zagona et al., 1998, 2001). For example, DSF is a tool designed for long-term planning for the Mekong River basin and RiverWare is a general river and reservoir modelling tool with both operational and planning applications. While these new initiatives are a step in the right direction, there is still much to be done to make the tools generic across different regions/jurisdictions and flexible enough to incorporate new scientific knowledge and approaches.

Where interactions between domain-specific models (e.g. MODFLOW (McDonald and Harbaugh, 1988); REALM; IQQM, MSM-Bigmod, WATHNET (Kuczera, 1997) and rainfall-runoff (RR) models) are important, a manual approach ('loose coupling') is often adopted for integrating the results from the different domains (e.g. Yang and Podger, 2010; Cuddy and Fitch, 2010; Gijsbers, 2010). Although more complex, integrated systems are better able to account for the full water balance. Good practice would use this flexibility to identify the dominant processes impacting on the water balance. Subsequent calibration would focus on modelling these processes in a robust and defensible way. In theory, this would reduce the unknown components of the water balance, arguably reduce model overfitting and result in a more robust and defensible calibration. However, greater flexibility can increase the opportunity for model overfitting, allowing the user to make a more complex model than justified by the available data. Consequently, good modelling practice is fundamental to getting the most out of an integrated modelling system and in building a robust and defensible model. Case study 2 (Section 4) demonstrates the potential benefits from using the integrated modelling system.

The need for reliable water information and water resources assessment is well recognised by the Australian Government. The National Water Initiative (NWI, 2004) was set up by the Commonwealth of Australia with the main objective of achieving a nationally compatible market, regulatory and planning based system of managing surface and groundwater resources for rural and urban use that optimises economic, social and environmental outcomes. The Commonwealth and the various state jurisdictions require a transparent, robust and repeatable tool to underpin water planning and management. To meet these needs, the Source Integrated Modelling System (IMS) is being developed by the eWater Cooperative Research Centre (CRC) in collaboration with several of its research and industry partners. It provides for the prediction and quantification of water and constituents from catchments to the sea. The project is funded by the eWater partners as well as the National Water Commission (NWC) and the Australian Federal Government's Department of Innovation, Industry, Science and Research and Department of Sustainability,