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A simulation tool for managing environmental flows in regulated rivers

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ABSTRACT

Environmental flows provide river flow regimes to restore and conserve aquatic ecosystems, creating considerably different demands compared to conventional water extraction. With increasing incorporation of environmental flows in water planning worldwide, governments require decision support tools to manage these flows in regulated rivers. We developed the Environmental Water Allocation Simulator with Hydrology (eWASH), a fast, flexible and user-friendly scenario-based hydrological modelling tool, supporting environmental flow management decisions for single- or multi-reservoir systems. Environmental flow demands and management rules are easily specified via the graphical user interface, and batch processing functions aid in uncertainty assessment. eWASH modelled main processes of complex regulated rivers and the tool is widely applicable. We calibrated eWASH for the Gwydir and Macquarie Rivers of Australia's Murray–Darling Basin. Modelled monthly environmental flow allocations exhibited Nash–Sutcliffe efficiencies of 0.55 for the Gwydir and 0.72 for the Macquarie catchments respectively when validated.

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1. Software availability

Package: Environmental Water Allocation Simulator with Hydrology (eWASH)

Availability: From the Centre for Ecosystem Science, University of New South Wales, Kensington, 2052, Australia, +61293853442

Cost: Free

Description: Tool for scenario-based simulation of environmental flow management

Program language: Python

Program size: 324 kilobytes

2. Introduction

Rivers are complex systems sometimes extending for thousands of kilometres with flow regimes governed by interacting climate, management and land use processes. Storages (dams, reservoirs) regulate most of the large rivers of the world (Nilsson et al., 2005) by capturing and releasing water mainly for human needs including water supply, hydroelectricity generation, flood mitigation and transport. This fundamentally alters natural flow patterns, affecting downstream flow-dependent ecosystems and leading to a global decline of aquatic biodiversity (Millennium Ecosystem Assessment, 2005).

In recognition of these problems, governments worldwide have protected flows exclusively for freshwater ecosystem health (Le Quesne et al., 2010). Environmental flows refer to the quality and quantity of water required to sustain freshwater ecosystems and their services to humans (Brisbane Declaration, 2007). These naturally variable flows provide periodic wetting and drying of channels and floodplains, nourishing aquatic habitat, supporting life cycles of freshwater organisms and dispersing biota, nutrients and spores (Ward, 1989). Environmental flows are considerably different in variability from flows affected by human needs, characterized by modifications in natural hydrological variability. With protection of environmental flows in regulated rivers worldwide, a fundamental challenge is delivering environmental flow regimes within the management and operational reality of regulated rivers.

In regulated rivers, environmental flows are held in storages and released to provide a flow regime for downstream ecosystems. Strategies for managing environmental flows are usually based on ecological objectives and environmental flow requirements (Dyson et al., 2003), but they also depend on sufficient water availability.

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Environmental flow allocations (availability, provisions) are the volumes of water periodically available for the environment. Allocations are rarely fixed amounts, they varied with water availability. Estimates of allocations is important to ensure the desired environmental flow regime is feasible, given the uncertainty in water availability and demand. Estimates of allocations would also help evaluate short-term release decisions, such as the need to release flows for immediate benefit against the need to conserve flows for future benefit. However, estimating environmental flow allocations is a major challenge, given dependence on spatially and temporally dynamic factors including climate, meteorology, land cover and water management (Hirji and Davis, 2009). Estimating allocations is not simply about supply. Release of environmental flows and other supplies may alter storage dynamics including evaporation and spills, affecting allocations (Hughes and Ziervogel, 1998; Judd and McKinney, 2006).

Further, not all release strategies are feasible because of physical constraints and management rules affecting river flows. Physical constraints such as storage outlet, spillway capacity and floodplain infrastructure prevent passage of large flows between storages and downstream ecosystems (MDBA, 2013; Steinfeld and Kingsford, 2013). Large flows may also pose flood risks to downstream properties. River operating rules may restrict flow volume or timing, or limit volumes of environmental flow accumulating in storage. These factors affect achievement of ecological requirements in regulated rivers around the world. Ultimately, managers need to evaluate the availability of environmental flows and constraints affecting releases of environmental flows in regulated river systems, given the uncertainty in availability and complex interactions with river management and operation.

Decision support tools should integrate these elements but existing hydrological modelling tools do not adequately support operational environmental flow decisions in regulated rivers. Scenario-based tools developed to support water management decisions, including HEC-5 (USACE, 1998), MIKE SHE (Graham and Butts, 2005), WEAP21 (Juizo and Liden, 2010) and WRAP (Wurbs, 2005), often have fixed demands, modelling environmental flows with flows for human needs, ignoring important differences between the two. Software for modelling river systems (e.g. REALM (DSE, 2009), IQQM (Simons et al., 1996), Source (Welsh et al., 2013) and WRYM (Juizo and Liden, 2010)) may be programmed to incorporate environmental flow but do not provide sufficient flexibility to enable users to manipulate volume and variability of releases or identify constraints affecting environmental flow releases. Environmental flow software that allows for modelling of different release scenarios may be simplistic (CSIRO, 2010; Hughes and Ziervogel, 1998). For example, release strategies were quantified by three simple abstraction scenarios in the River Wylye, United Kingdom, from no abstraction to full abstraction (Acreman and Dunbar, 2004). Other approaches rely on first identifying water availability then determining release strategies (Hughes and Mallory, 2008). Assessment tools such as Hydrologic Alteration Software (Mathews and Richter, 2007), eFlow tool (Marsh and Pickett, 2009), the Global Environmental Flow Calculator (Smakhtin and Eriyagama, 2008) and the integrated framework (Hughes and Louw, 2010) need to be coupled with operational tools to provide information about allocations and constraints for eventual implementation of environmental flows in regulated rivers. Water allocation models linking science and decision making (e.g. Water Allocation Decision Support System (Letcher, 2005), Economical Reallocating Water Model (Elmahdi et al., 2007) and SAHRA Integrated Modelling (Liu et al., 2008)), inform trade-offs in water planning, management and use but do not include environmental flows. Decision support tools modelling the allocation and release of environmental flows in real management contexts are lacking for managing environmental flows in regulated rivers.

We developed a scenario-based simulation tool for managing environmental flows in rivers where these flows are specified by management and regulated through storages. The goal of this tool was to quantify allocations and release constraints to support management of environmental flows in regulated river systems. The tool needed to incorporate hydrological variability and complex interactions between storage behaviour, demands of water users and water management. Importantly, volume and variability of environmental flow releases needed to be flexible, allowing users to simulate and assess management scenarios. Finally, the tool needed to be simple to implement and computationally efficient with functions to batch process large datasets to aid uncertainty analysis, a key element of decision making in complex systems (Hughes and Louw, 2010).

We describe the development of the decision support tool, Environmental Water Allocation Simulator with Hydrology (eWASH), and its application in two regulated rivers, the Gwydir and the Macquarie Rivers of Australia's Murray–Darling Basin (the Basin; Fig. 3). eWASH represented generic and specific elements of rivers, allowing for application in multiple systems and management relevance. Generic elements used common parameters which can be estimated for river systems in general, such as storage balance function, water accounting rules and demand generation. Specific elements were only applicable to specific river systems and included the water allocation framework, water accounting rules and river operating rules in the Gwydir and Macquarie Rivers.

3. Material and methods

3.1. Model structure

eWASH consisted of three interlinked sub-models, representing storage behaviour, water management and demands (Fig. 1). The storage behaviour sub-model accounted for physical and climatic processes influencing storage volume. Inputs into the storage behaviour sub-model were daily time series (inflow, rainfall, pan evaporation at storage), time series of releases generated within eWASH, and a storage capacity constant. Storage volume and spills were output from the storage behaviour sub-model into the water management sub-model for estimating allocations. The water management model reflected the allocation framework and rules governing water rights and water accounting. Inputs were decision variables for water licences and accounting rules, and orders generated within eWASH. Volumes available in accounts were output from the water management sub-model into the demand sub-model. This sub-model incorporated the basic factors driving water consumption for agriculture, domestic use, the environment and requirements for river operation. Inputs were volume and variability of environmental flow licences (environmental flow demand), historical water orders and tributary inflows (extraction), rules for flood operations and water transfers (river operation) and constants for outlet and spillway capacity. Daily releases were output into the storage behaviour sub-model. Storage behaviour and demand sub-models looped on a daily time step, and the water management sub-model looped on a monthly basis (Fig. 1). Additional datasets were required for calibrating the release function (historical orders, storage releases and tributary inflows) and the rating curve (storage surface area at corresponding storage volumes).

Sub-models included generic elements applicable in many regulated rivers, and elements specific to particular regions (Fig. 1). Elements in the storage behaviour sub-model used the generic mass balance equation to track water in closed systems, an

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