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Optimization tools for environmental water decisions: A review of strengths, weaknesses, and opportunities to improve adoption

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ABSTRACT

Public investment in river restoration through environmental watering has increased substantially in recent years. To sustain public support for such investment, management of environmental water must achieve the best possible outcomes in a transparent and defensible manner. The current management of environmental water relies on the ability of managers to estimate the impacts of their decisions under complex scenarios, often with multiple interdependent decisions that span over different spatial and temporal scales. Optimization modeling has been widely used in other forms of conservation management and an increasing body of literature documents the development of optimization models that could be used to improve environmental water decisions. This paper reviews this disparate research, showing that there are a range of different questions addressed using this modeling approach and that the representation of environmental outcomes varies. Future work must focus on improved adoption through engagement with end users and stakeholders during model development.

Contents

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1. Introduction

The growing human demand for water is placing increasing pressures on the worlds' water resources and ecosystems (Vorosmarty et al. (2010), with projected growth in food demand and irrigation likely to further stress water resources in many regions. There is wide recognition and growing political will to balance requirements for human water use with conservation of instream environments (Richter, 2014; Pegram et al., 2013; Hart, 2015), resulting in increased public investment in providing environmental flows (PC, 2010). To justify and protect this public investment, it is important that environmental flows are managed to achieve the best possible outcomes in a transparent and defensible manner.

Many methods have been developed to determine 'environmental flow' requirements (Tharme, 2003; Arthington, 2012). However, translating ecological principles and knowledge into operational decisions for environmental flow delivery remains a formidable challenge (Harman and Stewardson, 2005). Environmental water managers all over the world are being asked to achieve the best outcome with limited resources, and so methods that can trade off and balance competing environmental watering objectives are urgently needed (Acreman et al., 2014; Richter, 2014; Poff et al., 2015). The most common decision-making approach for environmental water delivery is based upon the accumulated experience of managers – so-called 'experience-based practice' (Cook et al., 2010). Decisions rely on the ability of managers to analyze complex scenarios, often with decisions nested within spatial and temporal dimensions (Turak and Linke, 2011). If considering even a single storage release, then an allocation may be delivered as one of an infinite number of potential sequential releases, all of which influence flow event magnitude, duration, seasonality, inter-annual variation and rates of change of flow at multiple downstream locations. The decisions are further complicated by the presence of: multiple points at which flows might be manipulated by dams, weirs or diversions; interactions with releases for consumptive users; and uncertain tributary inflows. Assessing the ecological consequences of these complex environmental flow decisions should ideally recognize that river "macrosystems" are hierarchical dynamic networks, influenced by strong directional connectivity that integrates processes across multiple scales and broad distances through space and time (McCluney et al., 2014). The complex interactions of these dynamic river macrosystems make environmental water decisions particularly difficult to undertake with informal, experience-based, approaches to decision-making. The increase in the number of countries that hold environmental water rights or reserves that require active ongoing management of water has highlighted these challenges (Le Quesne et al., 2010; O'Donnell, 2013). For example, in Australia, there are environmental water managers with a legal responsibility to manage environmental water rights in a transparent and accountable way (Commonwealth of Australia, 2007). They are looking to decision frameworks and support tools to improve the **consistency** and **transparency** of their decisions. The complexity of the decision space lends itself to the use of decision support tools. Such tools build on available data and expert opinion to model the link between the available management decisions and the environmental objectives. In this review, we examine existing optimization based decision support tools that focus on environmental water release decisions, using a range of optimization techniques. There are a number of other modeling tools that are used to assist in water planning decisions (for example, Multi Criteria Decision Analysis used in Ryu et al., 2009) however this paper focuses on the increasing use of optimization to address environmental watering decision making.

The use of analytical capabilities, data and tools to help tackle complex environmental problems has greatly increased (Gomes, 2009). One method is optimization modeling, which has been widely used to share water resources across multiple and competing consumptive users (Labadie, 2004) and in conservation management (Sarkar et al., 2006). Optimization modeling has the potential to support and inform the more informal decision making approaches, improving both the efficiency and transparency of decisions (Liebman, 1976; Maier et al., 2014). Even though the complexity of environmental systems is sometimes raised as limiting the usefulness of decision support tools (Rizzoli and Young, 1997), many of the challenges involved in representing environmental systems (e.g. dynamics, spatial coverage, complexity of interactions, randomness, periodicity, heterogeneity, scale and paucity of information; Guariso and Werthner, 1989) also exist in other fields where optimization has been readily adopted. There is a growing body of literature examining optimization as a tool for improving environmental water management. This paper (Section 2–5) synthesizes this existing effort, identifying common approaches, strengths, weaknesses and gaps. Importantly, this review focuses attention on literature that has viewed environmental water releases as a decision, not as a constraint. Chief among our conclusions (Section 6) is that almost none of this research has yet been used to inform actual environmental flow management decisions. This research therefore remains at the proof-of-concept phase and awaits the transition to uptake by water management practitioners. A future focus on adoption is vital if such research is to make this shift and have practical impacts on the way environmental water is managed.

2. Review of existing optimization models - literature search

We used a combination of search terms "environmental flow" or "environmental water" with "optimization" or "optimisation" in Thomson ISI web of science, Science Direct, JSTOR and Google scholar. Additional papers were located by searching bibliographies of papers found during the search – a 'snowball search', and through the professional knowledge and peer networks of the authors (Greenhalgh and Peacock, 2005). We only considered studies with an active decision variable concerning the volume of water released from storage for environmental purposes. This excludes studies that include legislated environmental water requirements modelled as constraints rather than decision variables. For example, in a review of storage models for hydropower generation, Jager and Smith (2008) found that nearly half of the models included environmental flows as a constraint on minimum flow releases. Where environmental flows are included as a fuzzy constraint, (i.e., there is still a decision around the quantity of release, albeit not through a decision variable), the study was included in this review. We excluded a number of studies that consider other aspects of managing environmental water, such as management of infrastructure associated with environmental watering (e.g. Higgins et al., 2011), or the least cost approach to acquiring environmental water (e.g. Hollinshead and Lund, 2006). Overall, 42 studies fulfilled the inclusion criteria, with more than half published since 2012 (Fig. 1).

3. What questions and timescales do the studies address?

With the broad challenge of "improving environmental water delivery", there is a suite of questions that an optimization model could answer. Broadly, models have targeted the following questions (not necessarily in isolation).