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Using optimization to develop a "designer" environmental flow regime

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ABSTRACT

There are increasing numbers of rivers with large storages, resulting in changes to environmental condition downstream. In these systems, environmental flow regimes that are specifically designed to meet environmental management objectives, whilst continuing to support economic needs, may be the best approach. A challenge remains as to how best to design these novel flow regimes. Decision support tools such as optimization provide a potential tool to achieve this. In existing tools environmental outcomes are not represented with sufficient realism and this is a major barrier to successful adoption by decision-makers. Here, we employ conditional probability networks as a promising approach that provides both ease of modelling and a direct link to ecological outcomes and processes. We present a generic model that can be used to represent any ecological endpoint within a river system. We then demonstrate the approach using two fish species in the Yarra River, Victoria.

1. Introduction

The worlds water resources are becoming increasingly stressed as human demand for water increases (Vorosmarty et al., 2010). Many of the worlds rivers are managed through infrastructure such as dams to help secure a reliable human resource for agriculture and urban centers, to manage flooding risk, and to support hydropower. Although estimates vary, there are currently in the order of 50,000 large dams worldwide (defined as those higher than 15 m), capturing around 20% of the natural river discharge to the worlds oceans (ICOLD, 2007). There are also a considerable number of smaller dams (Lehner et al., 2011), and in the order of 3700 new major dams in planning (Zarfl et al., 2015).

At the same time, there is a growing awareness of the impacts of these impoundments on instream environments, often as a result of altered water regimes (Dudgeon et al., 2006; Poff et al., 1997). These systems require managers to balance the human livelihood objectives supported by water and river development and the ongoing sustainability of the river ecosystems.

In these modified systems, the downstream environments remain valuable, but are significantly modified from their natural state. It therefore may be more appropriate to an environmental flow regime that meets the multiple objectives (consumptive and environmental) of the system rather than basing environmental flows on the natural flow paradigm (Acreman et al., 2014). *The idea of being able to define and quantify the components of the flow hydrograph and assemble them into an environmental flow regime that meets a particular set of ecological and social objectives can be thought of as a designer approach, producing environmental flows that support desired ecosystem states or provide desired ecosystem services* (Acreman et al., 2014, p 486).

A significant challenge however remains as to how to design and manage a flow regime to ensure that the complex needs of the environment are supported in the longer term (Acreman et al., 2014; Arthington et al., 2006; Arthington, 2012; Harman and Stewardson, 2005). This will require a trade-off between different river-level objectives (e.g. agriculture, hydropower, urban and environmental), and indeed between different elements of the environment (e.g. fish and vegetation). A water resource manager will need to decide how to operate the water resource system and its storages to achieve the best overall outcome for the environment and society (Poff et al., 2016). This challenge has been highlighted in Australia with the implementation and active and ongoing management of environmental water rights, which require

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an environmental manager to decide upon and implement flow releases continually throughout the year.

Optimization provides one approach for systematically and transparently developing a designer flow regime and assessing tradeoffs within a system. Indeed, an increasing number of studies have already applied optimization to the challenge of designing an environmental flow regime (for a review of these studies refer to Horne et al., 2016).

The consistent challenge for these studies is how best to incorporate and model the environmental objectives (Horne et al., 2016). An optimization tool must be able to assess the relative benefit of providing water to the environment at one time-step or location over another, between different environmental endpoints, or between the environment and other water users (depending on the model objective) (Horne et al., 2010).

While human water uses such as hydropower and agricultural water are generally trying to maximize relatively simple endpoints (e.g. electricity production, irrigated crop production), it is more complicated to develop a measure of ecological outcome from a flow regime. The approach must recognize the complex interaction between flow components and the nature of the non-linear flow responses (Horne et al., 2016, 2010). To date, methods have either allowed for non-linear flow responses but grossly simplified the aggregation of flow components (Chen, 2011; Horne, 2009) or have assumed a linear-flow response (Chang et al., 2010; Han et al., 2012; Ringler and Cai, 2006; Shiau and Wu, 2013).

Understanding relations between flow and ecology has improved in recent decades (Arthington, 2012). The highly complex and dynamic dependencies of aquatic flora and fauna, ecological processes and the multiple components of a flow regime (and the challenges in defining them) are discussed in an extensive and rapidly expanding literature (Arthington, 2012; Poff and Zimmerman, 2010; Webb et al., 2010). A clear challenge exists in translating or incorporating this complex knowledge into models that can inform management decisions.

In this paper we highlight the challenges and critical elements in representing ecological outcomes to support the design of novel environmental flow regimes. We then address the key question of how environmental outcomes can be incorporated into optimization-based decision support tools in a way that allows trade-off decisions. We propose Conditional Probability Networks (CPNs) as a possible way forward for representing ecological responses in such tools, and this is demonstrated through a case study.

2. The challenge of representing ecological outcomes

Optimization tools to support environmental flow design are mostly structured to include a model or representation of the physical water resource system and operational constraints, a model of ecological outcome or response to flow for each relevant species, and an objective function that links these species outcomes together considering spatial and temporal information. Here, we focus on the challenge of representing ecological outcomes and any implications for the objective function (shown in grey in Fig. 1). There is a clear trade-off between representing the ecosystem response in all its complexity, and developing a model that is manageable in its data requirements, implementation, computational complexity and interpretation of results. Ideally, we require an approach that:

- Shows the flow-ecology cause effect relationship (including the relationship between flow components)
- Shows the marginal benefit of flow
- Allows for links between ecological endpoints or species
- Allows for temporal sequences or changes in ecological outcome arising from past flow conditions and those likely to occur in the near future
- Is sufficiently computationally tractable to allow multiple endpoints or species to be considered simultaneously

A number of different approaches have been used to represent environmental outcomes in optimization-based decision support tools for management of flow regimes. Horne et al., (2016) reviewed optimization models where the environmental flow was part of the decision (i.e. where it is included as a decision variable). They found that most existing studies have adopted hydrological indicators as a surrogate for environmental outcomes (25 out of 40 papers). This most common approach to representing environmental outcomes is the simplest to implement (requiring no ecological data), but also the least ecologically realistic, with a number of limitations when applied within optimization (Horne et al., 2016). Firstly, in the context of developing a designer regime, hydrological indicators compare key elements of the regime to a target flow regime, usually based on the natural flow regime. The very premise of a designer regime is that a natural or unimpacted conditions are not necessarily an appropriate objective in systems heavily regulated by large storages /citepAcreman2014. Secondly, there is an implicit assumption of a linear response to changes in flow; for a given indicator of the flow-regime (usually a characteristic of the readily-available discharge flow time-series). For example, a high flow event might be characterised by the peak flow magnitude or total flow volume during the event, but this assumes that half the flow provides half the benefit. However, we know in reality that there will be non-linearities and thresholds (for example exceeding the height of the river channel) that affect the benefit of any component of the flow regime (Turner and Stewardson, 2014). This is a major limitation for trade-off decisions, because the shape of the marginal benefit curve (i.e. the benefit of each additional unit of water at a particular time) has considerable influence on how limited water is allocated between flow components (Horne et al., 2010). An assumption of linearity will affect this.

Ecological responses have been modelled directly using flow-response curves (Young et al., 2003). These relate a metric of ecological performance to variation in a single flow component. Such curves can include thresholds and non-linearities not possible with hydrological indicators. However, most ecological responses will be driven by combinations of different flow response curves, and flow components are rarely independent in their effects upon an individual species. A challenge of using flow-ecology response curves is how best to combine responses to individual flow components to provide an overall outcome for a particular species. Existing studies that have linked flow-ecology response models together have primarily used a geometric mean or the minimum of component measures as representing the most limiting factor (Marsh et al., 2007; Bryan et al., 2013). Other tools allow combination methods based on expert judgement usually in the form of weighting response curves (Young et al., 2003).

A limitation in these approaches is the failure to recognize event connectivity or interactions between species (Lester et al., 2011). To demonstrate this, consider how an optimization model would decide between a flow to trigger fish spawning and a flow to trigger recruitment back into the system. If the benefits of these two flow components are averaged, the model would assume the same outcome is achieved when providing one flow component and not the other as providing half of each. However, in reality, there will be no benefit of providing a fish recruitment flow if there has not previously been spawning. A further limitation is the assumption that the environmental response will remain constant over time.