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Optimisation as a process for understanding and managing river ecosystems

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A B S T R A C T

Optimisation can assist in the management of riverine ecosystems through the exploration of multiple alternative management strategies, and the evaluation of trade-offs between conflicting objectives. In addition, it can facilitate communication and learning about the system. However, the effectiveness of optimisation in aiding decision making for ecological management is currently limited by four major challenges: identification and quantification of ecosystem objectives; representation of ecosystems in predictive simulation models; specification of objectives and management alternatives in an optimisation framework; and evaluation of model results against actual ecological outcomes. This study evaluates previous literature in ecology, optimisation and decision science, and provides a strategy for addressing the challenges identified. It highlights the need for better recognition and analysis of assumptions in optimisation modelling as part of a process that generates and shares knowledge.

Contents

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1. Introduction

River regulation and water extraction have played a fundamental role in development through benefits such as improved water security for towns and agricultures, flood mitigation, hydropower, and transportation. However, previous river management practices have caused significant changes in the structure and functioning of rivers and floodplains, as well as changes to flow patterns, water quality and ecology (Poff et al., 1997, 2010; Bunn and Arthington, 2002). In response to the severe degradation of many of the world's rivers and the resulting social and economic cost, there has been a growing recognition of the importance of maintaining river systems and the incorporation of ecological objectives in river system management (Richter et al., 2006; Arthington et al., 2006; Acreman et al., 2014a; Poff and Matthews, 2013).

The greater recognition of the ecological value of river systems has introduced a number of challenges for the development of robust, adaptable and socially acceptable management strategies. Ecological objectives can be difficult to define and model, and often present a trade-off with other river management objectives such as agricultural yield or hydropower production. Optimisation is one method which can assist in identifying and evaluating alternative management policies, and trade-offs among multiple objectives. Whilst it has been widely applied to both water resource (see reviews by: Labadie, 2004; Nicklow et al., 2010 and Maier et al., 2014) and ecological management problems independently (e.g. Sarkar et al., 2006; Nicholson et al., 2006; Lee and Iwasa, 2014), fewer studies have utilised optimisation for the ecological management of river systems (e.g. Sale et al., 1982; Shiau and Wu, 2009; Suen et al., 2009; Yang and Cai, 2011; Rheinheimer et al., 2013).

The use of optimisation to aid decision making for ecosystems and other complex systems has been facilitated by the development of metaheuristics, a class of optimisation methods which use pre-defined rules to search for preferred solutions, and provide flexibility in problem definition. Metaheuristic methods overcame many of the restrictions on problem formulation and complexity required by earlier methods, such as linear and dynamic programming. However, the application of optimisation to increasingly complex systems has also required it to be redefined: from a tool used to find a single definitive solution; to one which aids in the exploration of different possible solutions, and facilitates learning and communication (Jacoby and Loucks, 1972; Liebman, 1976; Walters and Hilborn, 1978; Brill, 1979).

The focus on finding a single 'optimal' solution was often appropriate for early applications of optimisation, which were largely simple engineering or logistical problems. However, the concept of optimality becomes less clearly defined for complex systems, where there are multiple, ill-defined and often conflicting objectives, which can only be partially represented in a modelling framework. The optimisation of these systems requires greater consideration regarding problem definition, model representation, and the impact of uncertainties and assumptions on actual management outcomes (Liebman, 1976; Haimes and Hall, 1977; Brill, 1979).

The challenge of problem definition and representation of complex systems has been recognised and discussed in the context of planning and public policy since the 1960's and 70's (e.g. Hitch, 1960; Rittel and Webber, 1973; Liebman, 1976; Brill, 1979). These so called 'wicked problems' are applicable to ecological systems due to: inadequate knowledge of the system; lack of clear criteria by which to define objectives and measure outcomes; decisions having significant and often irreversible impacts; and each decision occurring in a unique context (Rittel and Webber, 1973; Metrick and Weitzman, 1998; Possingham et al., 2001; Failing and Gregory, 2003; Tear et al., 2005; Nicholson and Possingham, 2006, 2007; Game et al., 2008, 2014; Hirsch et al., 2011).

The use of optimisation introduces additional challenges through the need to specify objectives in a series of mathematical equations, and to develop an adequate model representation of the system such that 'optimal' solutions represent desirable outcomes to the actual problem (Ackoff, 1962; Haimes and Hall, 1977). This requires an understanding of how these formulations influence the resulting decisions, and consequently the management of the ecosystem (Wilson et al., 2009; Nicholson and Possingham, 2006). Whilst these challenges are well recognised, there has been limited discussion regarding the use of optimisation for ecological objectives in river basin management.

Defining ecological objectives is complicated by the existence of many and often conflicting social values regarding what is considered to be a 'preferred' environmental outcome. Preference for a particular outcome is also context dependent, and is influenced by factors such as a country's wealth, level of development, and competing requirements to fulfil basic needs. Added to this is the dynamic nature of many ecological systems, making it difficult to identify an ideal state in time and space. Representation of riverine ecological systems in a modelling framework requires an understanding of these dynamics and the relationship between river flow and ecological response, as well as the role of other influencing factors such as land management, climate, and disease (Shenton et al., 2012; Acreman et al., 2014b). It is therefore essential that the outcomes of any optimisation are critically evaluated in terms of the assumptions made, to identify what the likely actual outcomes will be. Assumptions can include conceptualisation of the problem, adequacy of the data, predictive capacity and suitability of the model for the decision being made, as well as set-up of the optimisation framework. Ideally, optimisation outcomes should be compared with actual ecological outcomes, to improve our understanding of ecological systems and improve the effectiveness of modelling and optimisation tools in aiding decision making.

Until recently, the majority of optimisation research has remained largely focused on algorithm development and application to different types of problems (Reed and Kasprzyk, 2009; Maier et al., 2014). Where optimisation has been employed to