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Analysis

A proposed framework to systematically design and objectively evaluate non-dominated restoration tradeoffs for watershed planning and management

David M. Martin [a,b,*], Virgilio Hermoso [c,d], Francis Pantus [d], Jon Olley [d], Simon Linke [d], N. LeRoy Poff [a]

[a] Department of Biology and Graduate Degree Program in Ecology, Colorado State University, Fort Collins, CO 80523, USA
[b] U.S. Environmental Protection Agency, Office of Research and Development, Atlantic Ecology Division, RI 02882, USA
[c] CTFC Forest Sciences Centre of Catalonia, Solsona, 25280, Lleida, Spain
[d] Australian Rivers Institute, Griffith University, Nathan Campus, Kessels Road, 4111, Queensland, Australia

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ABSTRACT

Human-driven alterations to freshwater ecosystems are leading to a global decline of river function and biodiversity. In our experience, managers want to be given many possible options to restore freshwater ecosystems that are workable within spatial, temporal, operational, and budgetary constraints of the system. Correspondingly, a new field for systematic river restoration planning has emerged through the use of well-established systems design concepts like multi-objective optimization and tradeoff analysis. In this article, we propose a decision framework for systematic river restoration planning where economic-environment systems design and tradeoff analyses are employed as a concurrent planning procedure before restoration interventions are implemented. Heuristic optimization and multi-criteria decision analysis methods are proposed to systematically design and objectively evaluate non-dominated economic-environment tradeoffs associated with restoration strategies within a watershed, and to provide a short-list of viable restoration alternatives to decision makers for negotiation and implementation. The proposed framework has the capacity to make science-based information and sophisticated decision support methods available for stakeholder deliberation. To illustrate the phases of the framework, we use a published case study of systematic restoration planning in South East Queensland, Australia.

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1. Introduction

The worldwide degradation of river ecosystem function and freshwater biodiversity (Strayer and Dudgeon, 2010) has led to the development of restoration strategies, which aim to rehabilitate the physical structure and ecological function of river ecosystems. The field of ecological river restoration has been comprehensively reviewed (USNRC, 1992; Palmer et al., 2014) and awarded substantial government funding (Bernhardt et al., 2005; Brooks and Lake, 2007). Yet criticisms of the practice of ecological river restoration are extensive. Scientific concerns include the scale of restoration projects, many of which are very local and restricted to river reaches with easy land access (Wohl et al., 2005; Beechie et al., 2010). Additional concerns are the failure to select functionally important ecological processes that contribute to successful restoration (Lake et al., 2007; Palmer et al., 2010) and a lack of post-restoration monitoring to evaluate success (Palmer et al., 2005; Roni et al., 2008). More general critiques include claims that integrated methods for planning restoration projects are under-utilized (Hermoso et al., 2012) and that philosophical approaches to restoration fail to consider key interactions (e.g., socio-economic, -environmental, -biological) to more comprehensively inform decision makers on how to evaluate restoration options (Hermoso et al., 2015).

Historically, decisions to implement river restoration were performed using ad hoc planning approaches where many different sources of information were gathered to develop actionable strategies with independently predicted outcomes (Hermoso et al., 2012). To account for this and other criticisms referenced above, planning for river restoration is becoming increasingly structured and systematic. Systems thinking approaches have emerged to better facilitate decisions to “wicked” (Rittel and Webber, 1973) resource management problems, which are characterized by competing stakeholder values, conflicting data requirements and metrics, spatio-temporal factors, and disagreement or incomplete knowledge on methodological assumptions. A compendium of frameworks are described for conceptualizing economic-environment interactions using systems thinking (Binder et al., 2013), and for including economic-environment interactions in resource management scenario planning (Munda et al., 1994). Others approach environmental systems analysis by developing generic but reproducible decision-making frameworks (Failing et al., 2013). Box 1 gives a general outline for planning approaches that address complex

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[*] Corresponding author at: 27 Tarzwell Drive, Narragansett, RI 02882, USA.
E-mail address: Martin.Davidm@epa.gov (D.M. Martin).

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Box 1

Step	Description
Problem definition	Focus group discussions to develop a common understanding of a complex watershed management problem
Conceptualization	Comprehensive understanding of the interactions of social and ecological system components (e.g., causal network diagram)
Restoration objectives	Agreement on outcome-oriented restoration objectives that are manageable, measurable, non-redundant, and socially and ecologically desirable for watershed planning (e.g., water supply, ecological habitat)
Design alternatives	Cause and effect models and expert opinion are used to develop restoration alternatives, where each alternative addresses the restoration problem with a unique set of interventions that trade off performance effects in the restoration objectives
Consequences	For each alternative, the restoration consequences are returned through predictive model responses or via expert opinion feedback
Value orientation	Individual or group stakeholder values may be incorporated into the tradeoff analysis
Prioritization	Formal tradeoff analysis of the restoration alternatives using decision making models and appropriate measures of uncertainty
Negotiation	Discussions aimed at reaching agreement on which restoration alternative(s) is preferred to implement
Adaptive management	Feedback process of implementation, monitoring, and re-evaluation

General steps in environmental systems analysis to support resource management decision making using river restoration as an example

environmental systems situations, which requires stakeholder involvement, understanding the dynamics and dependencies of social and ecological factors, development of cause and effect models to evaluate systems, and cyclical group learning.

Two complementary concepts in environmental systems analysis are seldom specified in a general decision support process but are noteworthy advances to progress the field of ecological river restoration. First, the principle of Pareto efficiency claims that decisions to enact change cannot make one party better off without making others worse off. This classical economics concept was used by Koopmans (1951) to mathematically analyze multi-objective choice problems. This was an important milestone to grow the field of multi-objective optimization, and it enabled the expansion of integrated methods to perform concurrent mathematical operations on many disparate cause and effect models. Modern approaches to artificial intelligence have aided growth in this field. Today, computer systems can use algorithms or heuristics to efficiently search through the space of feasible management consequences (i.e., geometric hyperplane where multiple management objectives are mutually satisfied) to find a set of so-called Pareto-optimal or non-dominated management consequences.

Dominance is bound by the logic that alternatives can be compared to one another using analytical methods such that less desirable alternatives can be eliminated from the decision situation and, as a result, preferred options are identified. The term non-dominated is used to refer informally to the fact that there exists a set of alternative consequences that trade off the desired performance effects of the management objectives, in other words, there is no solution from which the heuristic optimization solver can move toward which performs better for all objectives. Fig. 1 gives a simple example of how the Pareto efficiency principle may be applied to river restoration for multi-objective watershed management via restoration.

An important purpose of Koopmans' translation of the Pareto efficiency principle was to influence the design of resource management alternatives mathematically based on problem dimensions (i.e., continuous space between the upper and lower bounds of the objectives and constraints) without requiring social value orientations from decision makers (Goicoechea et al., 1982). In this sense, decision makers are encouraged to be involved in developing analytical models for the management objectives, but they don't pre-constrain the problem to a degree that only a limited set of management alternatives are feasible. This is an important approach to difficult watershed management problems because in our experience decision makers want to be presented with many feasible tradeoffs that are workable within spatial, temporal, operational, and budgetary constraints of a system, and they may not know what those options are without the support of systematic analytical models and advanced computer programs.

The second advancement that complements the Pareto efficiency principle is tradeoff analysis, which aims to investigate the tradeoffs among management consequences to find preferred or better options for stakeholder negotiation and implementation. The well-established domain of methods for multi-criteria decision analysis (MCDA) is specialized to perform systematic tradeoff analyses based on comparing discrete non-dominated options. Belton and Stewart (2002) distinguish three broad categories of methods for MCDA that vary by how they perform tradeoff evaluations: valuation, interactive, and outranking. A distinct characteristic of methods for MCDA is they all allow measures of relative importance (i.e., weights) of management objectives to motivate the tradeoff analysis, which is largely based on stakeholder preference orientations and/or expert opinions.

Valuation methods like the simple multiattribute rating technique (Edwards, 1977) and the analytic hierarchy process (Saaty, 1990) develop a comparable measure of value for each viable alternative. Weighted average models are used to estimate a utility or value function for each alternative, and a dominance relationship is established where alternatives are either more valuable than others (i.e., utility function scores are different among the set) or are indifferent to others (i.e., utility function scores are the same among alternatives). In contrast to valuation methods, interactive or “satisficing” (Simon, 1956) methods like compromise programming (Zeleny, 1973) use heuristic procedures to rank options in order of their desirability. Instead of establishing a value function, it is believed that a dominance relationship can be established that satisfies the constraints of the problem or are good enough for decision making. A way to elucidate this information is by incorporating aspiration levels, defined as specific performance effect values associated with desired or acceptable levels of the management objectives, into the tradeoff analysis. These models enrich our understanding of the dominance relationships among management tradeoffs without transforming the meaning of each alternative into a value. Outranking methods are especially useful when the underlying complexities of the problem are poorly understood. Traditional outranking methods like ELECTRE (Figueira et al., 2013) compare alternatives in pairs with emphasis on strength of evidence that one alternative is preferred over another.

In this article, we propose to incorporate the Pareto efficiency and tradeoff analysis concepts into a decision framework for systematic river restoration planning. The proposed framework combines modern planning tools like heuristic optimization and MCDA to inform a decision making process that is employed prior to implementing restoration interventions. We review the progress of ecological restoration in the literature relative to the framework, and we elucidate its potential value to inform decision making with an illustration that draws on