Environmental Modelling & Software 25 (2010) 1825–1836

Contents lists available at ScienceDirect

Environmental Modelling & Software

journal homepage: www.elsevier.com/locate/envsoft

Dynamic physical and economic modelling of riparian restoration options

Matthew A. Weber[a,*], Vincent C. Tidwell[b], Jennifer A. Thacher[c]

[a] University of Arizona, Department of Hydrology and Water Resources, 1133 E James E. Rogers Way, Tucson, AZ 85721, USA
[b] Geohydrology Department 6313, Sandia National Laboratories, PO Box 5800, Albuquerque, NM 87185, USA
[c] Department of Economics, MSC05 3060, 1 University of New Mexico, Albuquerque, NM 87131, USA

ARTICLE INFO

Article history:
Received 24 November 2009
Received in revised form
4 May 2010
Accepted 11 May 2010
Available online 29 June 2010

Keywords:
Dynamic simulation
River restoration
Benefit-cost analysis
Ecosystem service
Adaptive management
Choice experiment
Rio Grande

ABSTRACT

A dynamic simulation framework is used to compare benefit-cost ratios of riparian restoration investment strategies to pursue ecosystem service benefits. The model is meant to be adaptable to generic restoration planning applications, with the Middle Rio Grande riparian corridor in Albuquerque, New Mexico, U.S.A. presented here as the illustrating case. Model inputs include ecosystem service values from an original choice experiment, values from regional benefit transfer studies, and information from land managers.

The model includes three control variable modules: forest management, river restoration, and recreation infrastructure. Investment influences these modules, which in turn affect ecosystem service flows for the region. The model is exercised to compare a "No-Action" alternative with "Optimal Benefit-Cost Ratio" restoration funding. An extended sensitivity analysis explores a range of both physical and economic assumptions. The analysis has two major outcomes. The first is that directed restoration funding yields significant gains as compared with No-Action for all scenarios tested. The second major finding is that although optimized benefit-cost ratios are above unity for all "states of the world" tested, the ratio itself and funding patterns varied widely. These sensitivities underscore the need for a transparent adaptive management decision process supported by tools aimed not at deterministic prediction, but rather at structuring dialogue and inquiry into issues that defy simple intuition.

1. Introduction

The U.S.A. National River Restoration Science Synthesis lists over 37 000 restoration projects, with associated expenditures of over one billion dollars per year (Bernhardt et al., 2005). Physical modelling clearly forecasting the outcomes of restoration is not always available. Even more lacking are economic analyses to demonstrate that for the specific restoration strategies chosen, the benefits surpass the costs. Combining physical and economic modelling is vital to support transparent choices and to make the most of limited restoration spending.

This paper describes the challenges of building a dynamic simulation model to compare the benefits and costs of alternative riparian restoration management options.

Our approach shares elements with prior studies integrating physical and economic information for natural resources decision-making. Liu et al. (2008) comment on the increasing need to connect natural and social science to environmental decision-making generally, and describe a scenario-based modelling strategy. Argent et al. (2009) describe development of a water quality decision support system for a case study catchment, and Reichert et al. (2007) develop a general decision support model for river rehabilitation, stressing the importance of a transparent reference for scientific assumptions and stakeholder values. Marinoni et al. (2009) introduce a multi-criteria analysis tool intended to manage environmental systems for maximum aggregated benefit under a constrained budget. See Ward (2009) for a generalized hydro-economic model that includes optimization, as well as a review of how benefit-cost analysis has been used in water planning.

Benefit-cost analysis of restoration is aided by increasing prevalence of non-market valuation studies to quantify public values for environmental changes. Of the studies cited above, only Ward's (2009) framework would directly incorporate these currency-referenced values. Non-market valuation has matured as a subdiscipline of environmental economics with some studies dealing specifically with quantifying ecosystem service benefits of river restoration; for U.S. examples see Loomis et al. (2000), Holmes et al. (2004), Collins et al. (2005), and Weber and Stewart (2008). However valuation studies can be incomplete: those focusing on

* Corresponding author. Present Address: U.S. Environmental Protection Agency, 200 SW 35th Street, Corvallis, OR 97333, USA. Tel.: +1 541 754 4315; fax: +1 541 754 4799.

E-mail addresses: weber.matthew@epa.gov (M.A. Weber), vctidwe@sandia.gov (V.C. Tidwell), jthacher@unm.edu (J.A. Thacher).

1364-8152/$ – see front matter Published by Elsevier Ltd.
doi:10.1016/j.envsoft.2010.05.017

benefits typically do not include a detailed treatment of restoration costs, obviously a crucial factor. Restoration cost data are somewhat rare as noted by Jenkinson et al. (2006). Two studies in this issue display the importance of cost data in related contexts: see Marinoni et al. (this issue) for a riverine study featuring cost utility analysis, and Stoms et al. (this issue) for an investigation of how including land cost (and land vulnerability) information increase the efficiency of conservation purchases.

Valuation studies are typically static, referenced to a single point in time. Relatively few dynamic valuation case studies have been published; for exceptions see Higgins et al. (1997), Van Beukering et al. (2003), and Spring and Kennedy (2005). Other dynamic simulation contributions have been theoretic (Bockstael et al., 1995, 2000; Costanza and Ruth, 1998; Low et al., 1999; Eppink et al., 2004; Winkler, 2006a,b; Victor and Rosenbluth, 2007; and a special issue of Ecological Economics, vol. 41, 2002).

Our case study is the riparian corridor along the Rio Grande in Albuquerque, New Mexico, U.S.A., known locally as the "Bosque", a Spanish word for woodland forest. However, the modelling approach taken is purposefully generic and transferable with the addition of region-specific data. Regional models allow consideration of practical management problems and avoid scaling inaccuracies (Bockstael et al., 2000). Our model is built from a tailored valuation study, regional benefit transfer, and extensive stakeholder input. The model includes three control variable modules: forest management; river restoration; and recreation infrastructure. Investments influence these control variables which in turn interact with the natural system and modify the flow of ecosystem services. This project is part of a series of dynamic simulation planning tools under development for the Middle Rio Grande in the U.S. (see Tidwell et al., 2006).

In the succeeding sections we describe each of the physical model components in more detail as well as the techniques used for modelling restoration benefits and costs. The results of "No-Action" are compared with "Optimal Benefit-Cost Ratio" restoration funding. We then present an extended sensitivity analysis exploring a range of both physical and economic assumptions. Model results from this exercise vary widely, and in an interesting fashion, underscoring the need for an adaptive management approach to incorporate new data and system understanding.

This study is unique in three regards. First, the model is an interactive tool specifically designed for benefit-cost analysis of competing river restoration options. River restoration is increasingly common, but under-served by economic analysis. Second, we know of no other dynamic simulation model designed in tandem with a choice experiment survey. Thus, we are able to represent multiple public ecosystem service benefits from restoration, each of which is modeled as continuous variables changing incrementally as restoration proceeds. We consider sixteen possible restoration actions. Third, to our knowledge, this is the first valuation case study employing dynamic simulation of a desert region. Costanza et al. (1997) identified a general lack of desert valuation research with the summary value of $0 for the world's desert ecosystems. Our study features a riparian resource, arguably the most important fraction of desert lands.

2. Methods

2.1. Case study setting

This study is for the publicly managed riparian area along the Rio Grande (known as the "Bosque") defined laterally by constructed riverside levees, and stretching from the North Diversion Channel to the South Diversion Channel in Albuquerque, New Mexico, U.S.A. This area totals 1583 ha, but is a tiny fraction of the 56.5 million ha international Rio Grande Watershed (Fig. 1). In a desert setting such as this, riparian and wetland zones are especially important for the public land portfolio since surface-water oases are rare. Key managed resources associated with the Bosque include the forest, the river, and recreation infrastructure.

In the riparian forest, both tree density and vegetation type are of concern to managers. An exclusively dense forest has less niche diversity than a forest including open area. Denser forest also increases the likelihood of fire damage to adjacent residences. Vegetation types include native species such as cottonwood (*Populus deltoides*), coyote willow (*Salix exigua*), and New Mexico olive (*Forestiera neomexicana*), while non-native invasive species include saltcedar (*Tamarix ramosissma*), and Russian olive (*Elaeagnus angustifolia*). The distinction between native versus non-native vegetation is important because of aesthetic preferences, the types of wildlife supported by different plant species, different susceptibilities to fire, and the debate regarding water use by non-native versus native plant species. Management officials can affect vegetation density and tree-type by the decision to thin, clear, or preferentially revegetate native trees. The type of forest management chosen will incur different costs, and provide different levels of benefits for Albuquerque residents.

Historically, the Rio Grande was a sinuous and braided river with periodic spring floods and a freely migrating channel. The construction of levees and dams along the river limited flooding, arrested meandering, and caused bank incision, with significant impacts on native vegetation and wildlife. For example, native cottonwoods now experience increased competition with various invasive species. Although historically the U.S. Army Corps of Engineers (Corps) focused on stabilizing the riverbed and regulating river flows, efforts now focus on 'process-oriented' river restoration since natural processes of the river are restrained. These efforts include recreating a spring flood pulse, excavation to reconnect the incised river with the overbank, and removal of bank stabilization. River management in turn affects wildlife in the Bosque, a topic of concern for Albuquerque residents.

The Bosque is also a significant recreation site within Albuquerque, providing a unique urban park. It has biking and running trails and is a significant site for birding. The Corps plans to improve recreation infrastructure with new trails, toilets, parking areas, and picnic areas. Due to their central role in restoration planning, we utilize Corps resources, namely their feasibility plan (United States Army Corps of Engineers, 2003), subsequent personal communication with their staff scientists (United States Army Corps of Engineers, 2006), and the draft Bosque Community Model (United States Army Corps of Engineers, 2007).

2.2. Physical-economic model

The model is an accounting system for physical and economic variables (Fig. 2). The model is formulated according to system dynamics architecture (e.g., Sterman, 2000) and constructed in the commercial software package, Powersim Studio (Powersim Software, 2005); see Williams et al., 2009 for recent usage of the software in an environmental management context. Restoration is captured through financed investment (costs) to modify the environment through forest resources, river resources, and recreational infrastructure. A simple habitat model predicts impacts on wildlife that result from changes to the forest and the river. These changes and their direct and indirect outcomes affect public benefits. Simulations are on a yearly timestep and run for 100 years total (2006–2106) to allow consideration of long-term feedbacks.

2.3. Forest management

The forest module is organized around seven forest stocks, reported in hectares, with the sum being the total vegetated project area of 1583 ha (Fig. 3). Since vegetation density and tree-type capture the important distinctions in the riparian forest, the forest stocks are: 'Open Area', 'Intermediate Age Native Forest', 'Mature Age Native Forest', 'Intermediate Age Mixed Forest', 'Mature Age Mixed Forest', 'Intermediate Age Non-Native Forest', and 'Mature Age Non-Native Forest'. Open area is the least dense, and transitions through succession to an older, dense forest. A 'Mixed' patch indicates a combination of native and non-native trees. These seven patch categories are aggregated from the more detailed classification system of Hink and Ohmart (1984). Initial model values for each forest stock as well as forest dynamics are based on United States Army Corps of Engineers (2006).

Forest dynamics assumptions are summarized in Table 1. To account for the invasive character of non-native tree species, starting from open area the first stage of succession will yield 30% native, 30% mixed, and 40% non-native trees of intermediate age. To account for the faster growth rate of non-native tree species, native trees become intermediate in age after 10 years, and then become mature after an additional 20 years. Mixed and non-native trees become intermediate in age after 7.5 years and then become mature after an additional 17 years. Mature forest patches are reset to open area through natural decay and average fire conditions. As no significant difference in lifespan between native and non-native trees is documented, both are set at 100 years. However an order of magnitude difference in fire frequency has been suggested (Chuck Maxwell U.S. Fish and Wildlife Service fire forecasting, personal communication, 2007). For the base model, fire frequency was calibrated to be once every 1000 years for native patches and once every 200 years for mixed or non-native patches. This yields initial burn rates of 3 ha every year; yet in reality there is no average fire year. Most prior years showed only minimal fire damage in the study area while 2003 yielded approximately 100 ha burned.