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Implementation of holistic water resources-economic optimization models for river basin management – Reflective experiences

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Abstract

A holistic model embeds water resources and economic components into a consistent mathematical programming model, with the objective of maximizing economic profits from water uses in various sectors. Such a model can be used to address combined environmental-economic issues. Although holistic modeling represents a simple approach for building truly integrated water resources and economic models, it faces many difficulties in terms of temporal and spatial scale issues and model formulation, calibration, solution and result interpretation, as well as extensive data requirement. This paper addresses the difficulties involved in large-scale holistic modeling for integrated river basin management, and provides solution methods taking a self-reflective stance through a prototype model. This paper is a methodological paper for practitioners who are interested in integrated water resources-economic modeling.

Keywords: Water resources; Economics; River basin management; Optimization

1. Introduction

The study on water resources management at the river basin-scale usually involves multiple disciplines, and the purpose is to develop management programs that are physically based, socially acceptable and economically efficient. For a long time the complexity involved in the development and operation of rational management programs has pushed the development and application of effectively integrated models which include economic factors and hydrological processes. Also the sustainability issues of water supply and ecosystem functions in the basin context challenge the traditional engineering system design and operation, resource allocation, and investment policies, which call for innovative system-oriented analysis from the science community. Integrated hydrologic and economic models are well suited to assess combined water resources management and policy issues (McKinney et al., 1999; Letcher and Jakeman, 2003; Jakeman and Letcher, 2003; Lund et al., 2006; Letcher et al., 2007). In those models, hydrologic system operation, such as reservoir systems and stream–aquifer systems, is driven by an economic objective (or multiple objectives that include environmental and social goals).

There are two approaches to combine hydrologic and economic components – "compartment modeling" and "holistic modeling" (Braat and Lierop, 1987). The compartment approach treats hydrologic and economic components as separate sub-models, whose individual solutions are modified by some coordination methods. In holistic modeling, the sub-models are combined into a single consistent model, which is typically solved in its entirety, and information between components is transferred endogenously. The endogenous treatment of the inter-relationships between hydrologic and economic systems allows a more effective combined environmental-economic analysis (Cai et al., 2003a; Draper et al., 2003). Holistic models depict the coupled human–natural inter-relationships and mimic the impact of driving forces and feedbacks from the environment so that they can effectively

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analyze sustainability issues and support decision making involved in regional development.

Holistic water resources-economic models (HWEMs) have shown growing study interest and importance for integrated basin management. HWEMs are particularly useful for regions where competition for water is intense, economic water uses dominate, economic and operational impacts of proposed management alternatives are of interest, and data are available to calibrate supporting economic models (Marques et al., 2006). McKinney et al. (1999) reviewed the development and applications of holistic models for integrated river basin management in the past century. Since then a number of new holistic models and applications have been published, covering various problems in basin management, which have demonstrated the versatility of holistic models for integrated basin management. These new developments are briefly introduced in the following.

1.1. Water transfer through market

During periods of limited water availability, water market may serve as an efficient water allocator for all users defined by water rights. Actual water trade depends not only on water right regulations but also on hydrological variability and engineering feasibility. Engineering facilities such as storage and channels allow water buyers to access water and the lack of necessary engineering facilities may constrain the realization of water markets (Newlin et al., 2002). Within a basin or region context, spatial heterogeneity of water sources, return flows and water quality complicates the implementation of water markets. Traditional studies on water markets focus on the economic efficiency of the re-allocation of water through market. A holistic basin model provides a tool to simulate water markets with consideration of institutional, hydrological and engineering factors under a consistent modeling framework. The tool can assess both economic and environmental influences of a water market under various conditions including hydrologic levels, engineering systems, and transaction costs. Holistic models used for water market analysis include those provided by, but not limited to, Rosegrant et al. (2000), Draper et al. (2003), Ringler and Huy (2004), Jenkins et al. (2004), Booker et al. (2005), Ward et al. (2006) and Marques et al. (2006).

1.2. Infrastructure investment

River basin management faces a great challenge of making new guidelines for infrastructure investment toward economic efficiency, regional development, and sustainability. A holistic model can build the investment options of water supply and water use systems into the integrated hydrologic–economic context through cost functions. Several studies have demonstrated the feasibility of holistic models for evaluating water system infrastructure investment, such as Cai and Rosegrant (2004) on the effect of hydrologic uncertainty and Cai et al. (2006) on the influence of water markets on irrigation system investment in Maipo River Basin, Chile, Cai et al. (2003b) on irrigation system enhancement toward sustainability in the Aral Sea Basin in Central Asia, and Ringler et al. (2004) on the potential impact of dam investment on regional economic development in the Mekong River Basin.

1.3. Sustainable river basin management

Sustainable river basin management adapts to the dynamic human needs of land and water and natural functions for ecological systems and requires a thorough understanding of the complex interactions between land and water uses and ecological quality, especially the adverse impacts associated with those human activities that cause the degradation of ecosystems. Sustainability analysis for river basin management then needs to adopt a systems' approach. Holistic water resources–economic models that simulate coupled human and natural systems within a consistent system can be effective tools, which have been demonstrated for the determination of driving forces and the assessment of impacts from and responses to human interferences. Holistic models have been applied to analyzing: (1) the sustainability of irrigated crop production (Cai et al., 2002, 2003b; Rodgers and Hellegers, 2004; Jenkins et al., 2004; Booker et al., 2005); and (2) the hydrological–ecological sustainability concerning the limit of water quantity supply, water quality, and ecological functions (McCarl et al. (1999), Marques et al. (2006), Schoups et al. (2006), and Pulido-Velázquez et al. (2006) for groundwater sustainability; Cai et al. (2003b) for destination lake ecosystem; and Ringler and Cai (2006) for instream ecological water requirement).

1.4. Regional development

River basin management plays a critical role in regions where social and economic development depends upon water problems such as water use conflicts (e.g., typical upstream–downstream problems), droughts and floods, and the externality of water use (e.g., water pollution). Holistic models can show the details of economic and social impacts that match the requirement of decision making at the regional scale, which proves the necessity of integrated assessments in regional development. Case studies include, but are not limited to, the economic and environmental planning of South Central Texas (Gillig et al., 2001), the balance of hydropower and irrigation demand in the Syr Darya River Basin in Central Aral (Cai et al., 2003a,b), the trade-off between maximizing hydroelectric power generation and meeting navigation requirements in the Panama Canal system (Watkins and Moser, 2006), and the analysis of the heterogenic nature of interests and demands and equity in water supply among different regions within the Namoi River Basin (Letcher and Jakeman, 2003; Letcher et al., 2004).

Although the models listed above are reported to solve particular basin management problems satisfactorily, most modelers would agree with the difficulties involved in implementing large-scale HWEMs. Argent (2004) provided an overview of model integration for environmental applications, including the sciences and management imperatives,