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Integrated Water Resources Optimization Models: An Assessment of a Multidisciplinary Tool for Sustainable Water Resources Management Strategies

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Abstract

Integrated water resources optimization models (IWROM) are tools that have been developed over the last decade for determining optimal water allocations among competing sectors. This article describes the state of the art of IWROMs. We illustrate the various approaches that have been taken to determine and maximize economic benefits of withdrawing water for various use categories in IWROM applications, including off-stream human uses and in-stream uses such as ecological flows. First, we describe the hydrologic simulators used in IWROM applications, and the mathematical methods used to solve the optimization problems. It is suggested that IWROMs (a) seek to model coupled human–nature relationships and mimic the impact of water resources management strategies on the environment at the basin scale; (b) allow for the simulation and assessment of economic policies and strategies on water resources management; (c) can support basin-wide decision-making; and (d) are particularly useful for water-scarce regions. Finally, we have identify the need for improvements in (a) simulating biophysical systems; (b) handling model uncertainty; (c) inclusion of environmental flows and other relevant environmental factors through economic benefit functions; (d) accounting for social impacts related to shifts in water allocations among users; and (e) inclusion of stakeholders in the development of IWROMs.

1 Introduction

Pressures on water resources are increasing with the expanding scale of global development (Falkenmark and Rockström 2004). Impacts from these pressures range from ecological and hydrological consequences of over-allocation of river basins and groundwater aquifers, to public health consequences and ecological damage arising from water quality deterioration. The combined effects of these impacts tend to weaken positive relationships between water resources and economic development (Saleth and Dinar 2004).

Effective management of water resources concentrates on the problem of developing and managing multiple sources and use sectors while maintaining or improving ambient water quality. From an efficiency standpoint, water resources management involves the identification and development of water resources project investments that are net benefit-maximizing or at least cost-minimizing, while considering nonmonetized impacts, such as potential ecosystem degradation or negative social impacts. Water resources management and development involve not only physical measures, but political and economic measures, such as water pricing or marketing policies.

Engineering optimization approaches have been advanced and applied to a wide range of water resources management problems for decades (see, for example, Belaineh et al. 1999; Labadie 1997, 2004; Lund and Guzman 1999; Mayer et al. 2002; McPhee and Yeh 2004; Rao et al. 2004; Watkins and Moser 2006), with an emphasis on cost–benefit analysis of projects and operating strategies. More recently, integrated water resources optimization models (IWROM) have been developed to find optimal water allocation strategies when there is competition for water among the various use sectors. IWROMs attempt to introduce social, political, and ecological issues into traditional water resources engineering optimization schemes. The purpose of this article is to explore the conceptual basis, applications, and state of the art of IWROMs. We begin by reviewing the various approaches that have been taken to formulate objective functions and to value the economic benefits of withdrawing water for various use categories in IWROM applications. We describe the nature of the hydrologic simulators used in IWROM applications, and the mathematical methods used to solve the optimization problems. We end by suggesting that there are outstanding issues that remain in the field and by making some general conclusions.

2 IWROM

Solution of interdisciplinary water resources problems requires the integration of technical, economic, environmental, social, and institutional aspects into a coherent analytical framework. Since the 1960s, computational frameworks that combine optimization and simulation tools have been used to develop and assess water resources development strategies for decades (see, for example, Belaineh et al. 1999; Labadie 1997, 2004; Lund and Guzman 1999; Mayer et al. 2002; McPhee and Yeh 2004; Rao et al. 2004; Watkins and Moser 2006). While these previous works have produced significant advances in understanding interactions between economic objectives and physical constraints, the complexity of the systems considered in these works has been relatively narrow. IWROMs, also referred to by Cai (2008) as holistic water resources–economic models, include detailed information or submodels that represent the state of biophysical systems and transfer information between these components endogenously.

McKinney et al. (1999) provide the first description of the IWROM framework and suggest that IWROMs offer the opportunity to perform sophisticated economic and hydrologic assessments of water-allocation schemes. Since the review of McKinney et al. (1999), IWROMs have become more sophisticated, especially in the way that relationships between the economic and hydrologic components are described and in the complexity of the human–water system being considered. Table 1 gives a brief summary of a selected list of papers on IWROMs published since 2000, indicating the geographic region of application, the water supply considered, the categories of water use and associated economic benefits, and the goal of the analyses developed in the work. In the following sections, we review the nature of the objective functions, functions for evaluating economic benefit and valuation, hydrologic simulation models, and optimization solution methodologies employed in these works.

2.1 MAXIMIZING ECONOMIC BENEFIT

In the IWROM context, decision variables typically include flows associated with the water use or allocation categories of interest. Both out-of-stream and in-stream flows are considered; for example

$$\mathbf{Q} = (Q_i);\ i = C, A, R, I, H, E, Re \tag{1}$$

where $\mathbf{Q}$ is the vector of water withdrawals, the subscripts C, A, R, I, H, E, and Re represent crop or agricultural water use, water used in aquaculture production, residential water use, industrial water use, hydroelectric power use, water allocated for ecosystem functioning, and recreational use, respectively. Out-of-stream water uses are quantified as water withdrawn or water consumed. Return flows may be accounted for explicitly, but are frequently neglected.

The general problem of finding optimal water allocations may be formulated as

$$\max_{\mathbf{z}\in\Omega(z)} f(\mathbf{z}) \tag{2}$$

where the objective function f is assumed with a maximization convention, $\mathbf{z}(\mathbf{u},\mathbf{Q})$ consists of a vector $\mathbf{u}$ of state variables and a vector $\mathbf{Q}$ of decision variables, $\Omega_z = \Omega_u \cup \Omega_Q$ is the feasible region of $\mathbf{z}$ represented by a set of constraint equations, Ω_u represents the feasible region of $\mathbf{u}$, and Ω_Q represents the feasible region of $\mathbf{Q}$. The most commonly applied optimization framework is to solve for water withdrawal strategies that maximize the overall economic benefit (Booker and Young 1994), as in

$$\max_{\mathbf{z}\in\Omega(z)} EB = \sum_i EB_i(Q_i, \mathbf{u}) \tag{3}$$

where EB_i is the economic value, or benefit, associated with water withdrawal Q_i associated with sector i. The units assumed for EB_i here are currency per unit time (e.g. \$/month).

Table 1. Summary of Selected Applications of Integrated Water Resources Optimization Models.

Authors	Location of model application	Water supply sources considered in model	Water allocation sectors and associated economic benefits considered in model	Primary goals of model analysis
Rosegrant et al. (2000)	Maipo River Basin, Chile	Surface water	Agriculture, residential and industrial (combined), hydroelectric power production	Crop and crop area selection Sensitivity to variations in inflows, cost of improving irrigation technology, crop prices, salinity Assessment of water market trading schemes
Cai et al. (2002)	Syr Darya River Basin, Central Asia	Surface water	Agriculture, hydroelectric power production, ecological flows	Incorporation of risk and sustainability objectives Investments in infrastructure improvement Sensitivity to future increases in demands in various use categories
Cai et al. (2003a)	Syr Darya River Basin, Central Asia	Surface water–groundwater	Agriculture, hydroelectric power production, ecological flows	Investments in infrastructure improvement Impacts of taxes and subsidies Assessment of water trading schemes Sensitivity to variations in inflows, salinity, crop evapotranspiration, water price
Cai et al. (2003b)	Maipo River Basin, Chile	Surface water	Agriculture, residential and industrial (combined), hydroelectric power production	Irrigation efficiency as a function of improvements in technology and water allocation schemes Assessment of water trading schemes Sensitivity to increases in water demands, changes in water price
Draper et al. (2003)	Several California River Basins, USA	Surface water–groundwater	Agriculture, residential and industrial (combined)	Calibration to historical demands Determination of shadow values
Jakeman and Letcher (2003)	Mae Chaem Basin, Thailand Namoi River Basin, Australia Yass River Basin, Australia	Surface water	Agriculture	Sensitivity to climate, land use changes, water allocation strategies

Table 1. *Continued*

Authors	Location of model application	Water supply sources considered in model	Water allocation sectors and associated economic benefits considered in model	Primary goals of model analysis
Cai and Rosegrant (2004)	Maipo River Basin, Chile	Surface water	Agriculture	Influence of hydrologic uncertainty on selection of irrigation technology improvements
Jenkins et al. (2004)	Several California River Basins, USA	Surface water-groundwater	Agriculture, residential and industrial (combined)	Capacity expansion strategies Storage management strategies Water marketing strategies
Letcher et al. (2004)	Namoi River Basin, Australia	Surface water	Agriculture	Water allocation strategies
Cai and Wang (2006)	Maipo River Basin, Chile	Surface water	Agriculture	Calibration to historical water applications and crop acreages
Pulido-Velázquez et al. (2006)	Adra River Basin system, Spain	Surface water, groundwater	Agriculture, residential industrial (combined)	Conjunctive management of surface water and groundwater Water marketing strategies Estimation of opportunity costs associated with avoiding scarcity and providing ecological flows
Ringler et al. (2006)	Dong Nai River Basin, Vietnam	Surface water	Agriculture, residential, industrial, hydroelectric power production	Assessment of water market strategies Investment for improvements in irrigation efficiency
Ringler and Cai (2006)	Mekong River Basin, Southeast Asia	Surface water	Agriculture, residential and industrial (combined), hydroelectric power production, ecological flows, aquaculture production	Sensitivity to variations in inflows, environmental valuations, aquaculture production costs
Schoups et al. (2006)	Yaqui River Basin, Mexico	Surface water–groundwater	Agriculture	Conjunctive management of surface water and groundwater Irrigation infrastructure improvement
Ward et al. (2006)	Rio Grande River, USA and Mexico	Surface water–groundwater	Agriculture, residential, industrial (combined)	Water marketing schemes Sensitivity to variations in available water supply (drought severity)

2.2 DETERMINATION OF ECONOMIC BENEFITS

The valuation of water for various economic sectors is the subject of intensive studies by natural resources economists; no one approach within and across sectors has been found to be universal. Economic benefits can be calculated with production functions that estimate the value of producing of water-dependent goods as the price that can be obtained for the goods less the cost of producing the good, including the cost of procuring water. For example, for agricultural crops, these models are typically relatively simple; e.g.

$$EB_C = \sum_{i_c} Y_{i_c}(Q_{i_c})[P_{i_c} - C_{i_c}(Q_{i_c})] \tag{4}$$

where EB_C is the economic benefit associated with producing irrigated crops; Y_{i_c} is the yield of crop i_c; P_{i_c} is the selling price of crop i_c; and C_{i_c} is the cost of producing crop i_c, including the cost of purchasing irrigation water, in addition to labor, equipment capital and operation and maintenance costs, and chemicals. The presence of the yield function in equation (4) indicates that agricultural output and its associated value are directly tied to water availability. Many empirical relationships have been derived for $Y_{i_c}(Q_{i_c})$ (see, for example, Letey et al. 1985). Economic benefits associated with aquaculture production have also been estimated with a production function approach, where the value of the fisheries is related to in-stream flows (Ringler and Cai 2006).

Equation (4) does not incorporate a price–demand relationship for irrigation water, implying that the cost of irrigation water is negligible with respect to other crop production costs. For other use sectors, however, such as residential use, an equilibrium water price–demand function is typically used. A typical residential water price–demand relationship function is shown in Figure 1, where

$$Q_R = cP_R^{\varepsilon} \tag{5}$$

and where Q_R is the residential, or household, water demand, P_R is the residential water price, ε is the elasticity, and c is a constant. Given an appropriate price–demand relationship, as in equation (5), the residential economic value, EB_R is equivalent to the trapezoidal shaded area in Figure 1, or

$$EB_R = \int_{Q_R}^{Q_{R,0}} P_R dQ'_R \tag{6}$$

where $Q_{R,0}$ is the initial water demand. Equation (6) is equivalent to the apparent willingness to pay (WTP) to avoid a reduction of water supply from $Q_{R,0}$ to Q_R. The residential economic value is sometimes expressed as the difference in WTP and the cost of producing the incremental amount of water (referred to as the consumer surplus; Young 2005), or

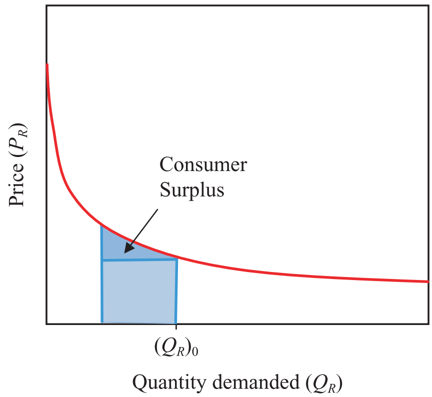

Fig. 1. Example of price–demand relationship and estimation of willingness to pay.

$$EB_R = \int_{Q_R}^{Q_{R,0}} P_R dQ'_R - P(Q_{R,0} - Q_R) \tag{7}$$

The substantial literature on estimation of household demand functions for water has been summarized by many, including Arbués et al. (2003) and Olmstead et al. (2007). In equation (5), the price elasticity is a measure of the sensitivity of water demanded to changes in price (Young 2005). Price elasticities have been found to range from –0.10 to –0.36 in the United States and developing countries (Olmstead et al. 2007; Ringler and Cai 2006; Young 2005) indicating that water demand is relatively inelastic to price.

Industrial water use includes water used directly in a product (e.g. food and beverage processing) and indirect uses, such as for cooling, processing, and waste disposal. Industrial water demand is influenced by many factors, including the demand and prices for the goods being produced, labor costs, the technology available for production, and raw material input prices (including the price of water). Industrial users may purchase water from local water utilities or may be self-supplied, especially when uses are relatively large.

Industrial water demand can be modeled as

$$Q_I = Q_I(P_I, P_X, X) \tag{8}$$

where P_I is the price of water for the industrial sector, P_X are the costs associated with all other inputs (materials, labor, etc.), and X is the amount of product generated. The economic benefit associated with industrial water use is determined by integrating P_I against Q_I, as described earlier for residential use. Since water is typically a small portion of an industry's production costs, the price–demand relationship may be difficult to quantify.

Benefits associated with hydroelectric power production can be calculated with a production function, as in

$$EB_H = Q_H H_e E_f (P_H - C_H) \tag{9}$$

where Q_H is the flow released for hydroelectric power production, H_e is the effective head that the water drops as it passes through the turbines, E_f is the generator efficiency, P_H is the price of selling the generated electricity, and C_H is the cost of generating the electricity.

Finally, methods for determining economic benefits associated with the environment are perhaps the most complex, but least advanced, of all methodologies used to determine values in IWROMs. Economic benefits associated with the environment that have been explicitly incorporated into IWROM include ecological flows (Cai et al. 2002, 2003a) and wetlands maintenance (Ringler and Cai 2006). Although only a few studies have explicitly included environmental economics benefits, it is worth noting that environmental requirements have been incorporated into IWROMs by other means. Ecological flows have been incorporated either as 'hard' constraints, in the form of imposed minimum streamflows (Cai et al. 2003b; Draper et al. 2003; Jenkins et al. 2004; Pulido-Velázquez et al. 2006; Ringler and Cai 2006; Ringler et al. 2006; Ward et al. 2006), or 'soft' constraints, where the risk of not providing minimum streamflows is minimized (Cai et al. 2002, 2003a). Seawater intrusion into groundwater aquifers as a result of overpumping has been limited by imposing a constraint that groundwater heads cannot decrease below sea level (Pulido-Velázquez et al. 2006; Schoups et al. 2006). Salinity management (Cai et al. 2002, 2003a) has been addressed by minimizing the difference between target and predicted salinities and by imposing a tax on agricultural return flows as a function of salinity, which is subtracted from the agricultural economic benefit.

Economic benefits associated with recreation have rarely been incorporated into IWROMs. Ward et al. (2006) define economic benefit associated with recreational use, which is dependent on reservoir storage, rather than flow.

2.3 ALTERNATIVE VALUATION METHODS AND OBJECTIVE FUNCTIONS

Maximizing economic benefits associated with water use is the primary objective function that has been applied in IWROM studies. However, several modifications, additions, and alternatives to equation (3) have been applied in IWROMs. First, several authors have included infrastructure improvement strategies for improving water efficiency. Cai et al. (2002) develop a function for calculating the ratio of the marginal improvement in economic benefit resulting from increases in water use efficiency to the corresponding marginal increase in infrastructure investment needed to produce the given level of water efficiency increase. This ratio is to be maximized and is incorporated into the optimization framework along with the objective of maximizing overall economic benefit. Cai et al. (2003a) also use the same marginal economic benefit to marginal investment ratio to assess the efficacy of various water efficiency gains. Cai et al. (2003b) use a range of irrigation efficiency indicators to assess selected water allocation schemes. Cai and Rosegrant (2004) use an objective function consisting of net economic benefit less irrigation technology cost. Irrigation technology cost is determined as a function of irrigation efficiency. Cai et al. (2003b) included a salinity tax, which penalizes salinity discharges from agricultural sites. The tax, estimated as a tax rate per salinity load times the salinity load emanating from a site, is subtracted directly from the economic benefit objective function. Ringler et al. (2006) tested different irrigation improvement scenarios.

Draper et al. (2003), Jenkins et al. (2004), and Pulido-Velázquez et al. (2006) apply objective functions where scarcity costs are to be minimized. Scarcity costs are defined as economic losses to users derived from water shortages in the consumptive demands. In other words, scarcity costs are equivalent to the WTP for water beyond actual allocations delivered (as determined by the model) and are determined by integrating a price demand curve from the maximum demand to the actual amount to be delivered.

Cai et al. (2003a) introduce sustainability criteria into an objective function that is assessed on a year-to-year basis. They translate various concepts of sustainable development to operational concepts that can be applied to the design and operation of water resources systems. The intention is to produce water-allocation schemes that are stable, yet flexible, over the long term while simultaneously mitigating negative environmental consequences from extractions. The criteria include various measures of risk (reliability, reversibility, and vulnerability), achievement of environmental targets related to salinity, equity (consistency of water allocations over time and demand sites), and economic benefit of water infrastructure improvements.

Several IWROM applications have been applied to analyze water marketing or trading schemes (e.g. Cai et al. 2003a,b; Jenkins et al. 2004; Pulido-Velázquez et al. 2006; Ringler et al. 2006; Rosegrant et al. 2000; Ward et al. 2006). These analyses typically involve developing shadow price–withdrawal relationships. The relationships are generated by running the models (outside of the optimization framework) for each demand site with varying water withdrawals and deriving the marginal value associated with each level of water withdrawal. The resulting relationships essentially indicate the WTP associated with a demand site or an entire water use sector. The models (using the optimization framework) are then solved with the WTP replacing, for example, the production function for agricultural benefit (equation 4). The models are applied to a range of schemes, from completely open markets, where water can be traded from any demand site to another, with no water rights restrictions, to allowing trading of water only up to a given water right. These analyses allow for comparison of total and sector-specific benefits among the different schemes.

2.4 HYDROLOGIC SIMULATIONS

The sophistication of hydrologic simulators incorporated into IWROMs varies widely. Typical applications involve simple, node-link, water balance models of river basins that include surface water reservoir systems; 'demand sites', where water withdrawals take place, corresponding inflows due to return flows, and linkages representing the river reaches between the reservoirs and demand sites. Figure 2 shows an example of a node-link network. These models typically operate with monthly time steps, where the hydrologic system is assumed to be at equilibrium within each time step. Short duration events, such as individual storm events, are usually not captured by these models. Flows in the link-node network are driven by runoff from sub-basins (via precipitation) entering the network at point locations, representing inflows from tributaries. The inflows enter the system on a time step–by–time step basis.

Jakeman and Letcher (2003) and Letcher et al. (2004) use a lumped parameter, rainfall-runoff model and stream routing model, which allows for climate as an input and simulation of river stages. Cai et al. (2003a) and Jenkins et al. (2004) use a single-tank model to simulate changes in storage in groundwater aquifer systems as a result of extractions. In the works of Pulido-Velázquez et al. (2006) and Schoups et al. (2006) on optimal allocations from a conjunctive surface water-groundwater supply, the groundwater system and stream–groundwater interactions are modeled explicitly, in addition to modeling a reservoir system via water balance.

A few IWROMs consider simulations of hydrologic phenomena other than flow. Cai et al. (2002, 2003a) simulate salinities in and transport between irrigation return flows, soil water, near surface groundwater and rivers using a simple chemical balance model. Jakeman and Letcher (2003) simulate erosion (soil loss) as a result of transformation from forest land to crop land. Soil loss is not included in the model as an objective to be minimized or as a constraint, but is calculated 'post-optimization'.

2.5 OPTIMIZATION SOLUTION METHODOLOGIES

As evidenced by the combination of objective functions, constraints, and hydrologic simulators described in the previous sections, most IWROMs are highly nonlinear and include a large number of decision variables. To relieve the computational burden, several IWROMs (Cai et al. 2002, 2003a; Rosegrant et al. 2000) break up the problem solution into multiple stages that are solved in sequential stages or into multiple stages that are solved in parallel but with different time steps. To solve the optimization problem, IWROM approaches have used nonlinear optimization solvers contained in the General Algebraic Modeling System high-level programming language (Cai and Rosegrant 2004; Pulido-Velázquez et al. 2006; Ringler et al. 2006; Ringler and Cai 2006; Rosegrant et al. 2000; Ward et al.

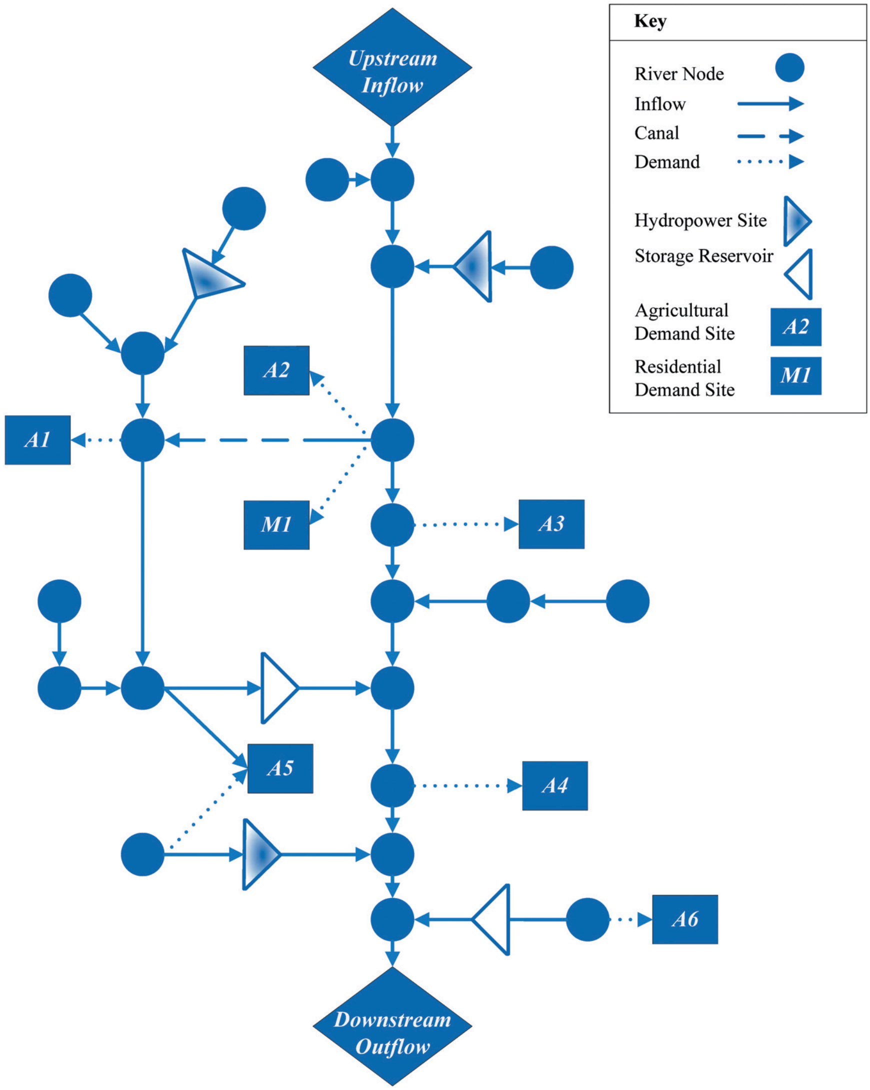

Fig. 2. Example of node link network for simulating a surface water system.

2006); a hybrid linear programming–evolutionary optimization methodology (Cai et al. 2002); and packaged network flow optimization solvers (Draper et al. 2003; Jenkins et al. 2004).

For nearly all of the IWROMs applied to date, whereas the optimization problem may be computationally intensive due to the nonlinearity of the problems and the number of decision variables involved, at least the simulators that are executed during the optimization sequence are relatively simple. Of all IWROM applications reviewed in this paper, only Cai et al.

(2002) have involved simultaneous consideration of multiple, conflicting objectives. Rather than use a multi-objective solution methodology, Cai et al. (2002) used a linear weighting approach to combine all of the objectives into a single objective. In their application, all weights were equal, implying that each objective was equally important.

3 Outstanding issues

The literature on IWROMs indicates that these tools have advanced and expanded quickly over the last few years and that these tools have the potential to make a significant impact on conceptual and practical approaches to water resources management. Cai (2008) discusses several issues to be considered for further improvements in IWROMs, including the potential need for more sophisticated hydrologic models, the importance of examining model uncertainty, and possible pitfalls in model calibration exercises. In the following, we expand on some of these issues and suggest that there are several other outstanding issues and areas where further advances could be made in IWROMs.

3.1 CONSIDERATION OF UNCERTAINTY

Specifying sources of error and making accurate estimates of uncertainty in the outputs of IWROMs can be very difficult (Jakeman and Letcher 2003). Sources of error in individual models may be difficult to identify and quantify, as is the case in the hydrologic simulators and economic models used in IWROMs, where the lack of data for model calibration and validation is commonly an issue. Because of the breadth and complexity of issues involved in an integrated model, 'the level of uncertainty goes beyond unexplained randomness to a situation where many things are fundamentally unknowable in a traditional, objective, scientific sense' (Rothman and Robinson 1997, cited in Jakemen and Letcher 2003). In addition, it is often that case that the propagation of errors through the IWROM is poorly understood, due to the complexity of feedbacks within the integrated system. Appropriate processes for validating IWROMs have yet to be fully developed; however, in a few cases, researchers have at least attempted to calibrate IWROMs to historical water demands (Cai and Wang 2006; Draper et al. 2003). All of these issues indicate that applications of IWROMs must be sensitive to the effects of uncertainty on the model results and more sophisticated approaches may be needed to quantify uncertainty.

Furthermore, models tend to be used to investigate scenarios that can be very different from the situation in which the model was calibrated and tested. The validity of the IWROM or component models outside these circumstances may be questionable and the level of uncertainty in predictions may be difficult to quantify. Rational procedures for choosing planning periods in

IWROM applications, which have ranged from 10 to 30 years, have not been established. The value of long-term applications of IWROMs is questionable, given the considerable uncertainty in many modeling aspects, especially the prices and costs include in the economics models. Scenario analysis may be used to explore model uncertainties in these cases. However, formulating realistic scenarios may be difficult, considering that temporal trends in many of the phenomena quantified in these scenarios (such as climate, land use and population change) may be nonstationary.

3.2 SOPHISTICATION OF HYDROLOGIC SIMULATORS

Most of the hydrologic simulators for modeling surface water flows use specified inflows taken from historical records to drive flow in the basin. While this approach is less data-intensive, it offers significantly less flexibility than using a rainfall-runoff model. Since many of the IWROM applications are used over planning periods that extend into the future, it would be useful to simulate the impacts of predicted land use and climate change on water availability. Land use changes can impact runoff generation, groundwater recharge, and evapotranspiration. Climate change implies that precipitation rates can change; evapotranspiration also is highly dependent on temperature and solar radiation. The use of climate change predictions and their impact on water resources is becoming more widely applied in recent years (e.g. Barnett et al. 2004; Burger et al. 2007; Dettinger et al. 2004; Fowler et al. 2007; Mauer 2007). In order to simulate these impacts, surface water flow models need to explicitly account for the portioning of precipitation into runoff, infiltration and evapotranspiration (Singh and Woolhiser 2002).

The majority of IWROM applications where groundwater supplies have been considered have relied on highly simplified groundwater models, for example, single-tank or tanks-in-series models (e.g. Cai et al. 2003a; Jenkins et al. 2004; Pulido-Velázquez et al. 2006). While groundwater models based on groundwater flow equations are data and, in some cases, computationally intensive (see Schoups et al. 2006), there is a danger that critical state variables will not be estimated correctly with simplified models. For example, since the costs associated with groundwater supplies usually depends strongly on depth to groundwater, it is important that local groundwater heads be calculated correctly.

Eventually, IWROMs should be able to account for the environmental and human health impacts associated with the return of water withdrawn for various use sectors. Thus, one of the next advancements in hydrologic simulations in IWROMs could be to include rudimentary chemical fate and transport modeling of return flows containing, for example, agricultural drainage and municipal and industrial wastewater. Output from chemical fate and transport models would consist of chemical concentrations or loadings. Once these quantities are estimated, they could be incorporated into objective functions (e.g. minimize chemical concentration at a control point) or constraints (e.g. chemical loadings cannot exceed a fixed target). It is also possible that the chemical loadings or concentrations could be transformed into environmental costs and included in a net benefit function. However, chemical fate and transport modeling are data intensive: chemical source terms, i.e. pesticide and fertilizer application rates, chemical transformation rates, hydrologic residence times, and inter-compartmental exchange rates are only some of the data needs.

3.3 Representation of benefits associated with environmental protection or restoration

Very few of the IWROM works considered here have explicitly accounted for economic benefits associated with allocating water for environmental purposes, and these applications have been relatively simplistic. At least two inter-related approaches can be applied to incorporate more sophisticated approaches for incorporating these benefits: nonmarket valuation and ecosystem services. There is a rich literature on nonmarket valuation of water associated with environmental purposes. Several researchers have estimated nonmarket values of in-stream flows for recreational use (e.g., Duffield et al. 1992; Sanders et al. 1991; Weber and Berrens 2006); preservation of endangered and at-risk native fish species (e.g. Berrens et al. 1996); bequest and existence values (e.g. Brown and Duffield 1995; Sanders et al. 1990); ecological integrity (e.g. Gonzalez-Caban and Loomis 1997); and combinations of environmental services (e.g. Holmes et al. 2004; Morrison and Bennett 2004; Ojeda et al. 2007). Water valuation for such uses requires a two-step process, including first the estimation of the value that people place on specific environmental in-stream uses, and second, the determination of the flow regime that allows these values to be maintained. However, both of these tasks are labor- or data-intensive, and can result in significant uncertainties.

Ecosystem services are the benefits humans receive, directly or indirectly, from ecosystems and are the direct product of coupled social–ecological systems (Costanza et al. 1997; Daily 1997). The concept of determining the value for ecosystem services as applied to water-resource allocation is rapidly emerging (Daily 2000) and has been applied in the IWROM context by Ringler and Cai (2006). Relevant nonmarket ecosystem values include waste dilution, maintenance of biodiversity, maintenance of wetlands and the services associated with wetlands, and maintenance of riparian vegetation. Typically, applications of ecosystem service concepts to water-resource allocation strategies involve estimating the values associated with an aquatic ecosystem under current and/or unregulated flow regimes and the potential reduction of this value as a function of reduced flows. The reduction in value can be added to an economic benefit function as a negative externality.

However, again, determining ecosystem value and potential changes in value as a function of flows is data-intensive and fraught with uncertainties. Whereas 'universal' ecosystem values have been developed (e.g. Daily 1997) and studies have been made to relate values to flows, these relationships are likely to vary significantly from place to place (Postel and Richter 2003). Payment for ecosystem services involves compensating resource users who adopt conservation or restoration practices (Chan et al. 2006; Naidoo and Adamowicz 2006; Wunder 2007). Presumably, the payment reflects the value of the resource being conserved or restored and could be included in a net benefit function.

3.4 INCLUSION OF SOCIAL FACTORS AND IMPACTS

Whereas the practice of economic valuation in IWROMs is relatively advanced, the inclusion of societal desires, realities, and impacts is not. Stakeholder participation in the development of IWROMs apparently has not been reported in the literature. Stakeholder participation could have several advantages. First, an interactive, transparent process in the development of IWROMS is more likely to result in adoption of the results of IWROM applications and eventual transformation into policy (Cai 2008). This is especially the case for relating the vision of stakeholders to quantitative criteria, such as objective functions and constraints. In addition, involvement of stakeholders in the development of process models (i.e. hydrologic simulators) may engender stakeholder confidence in the IWROM results. Second, efforts to involve stakeholders may reveal the important social and political institutions involved in water resources management in the study area. A critical assessment of the capacity of these institutions to support and incorporate management policies recommended by IWROMs is important for the success of IWROM applications.

Third, as IWROMs are applied more, they may involve consideration of multiple, conflicting objective functions. In these cases, stakeholders will need to be involved in either explicitly choosing 'importance' weights to be assigned to each objective function, or in assessing tradeoff curves generated with optimization frameworks relying on Pareto optimization. Fourth, allowing stakeholders to alter key assumptions where they feel results do not reflect realities on the ground, given that they may have a better understanding of uncertainties, is an important part of the IWROM development process, both for validation and for increased adoption of results and recommendations arising from the IWROM application (Jakeman and Letcher 2003).

Social impacts that may come from shifting water allocations among various use sectors should not be ignored. For example, in many cases, agricultural water use will not generate as high an economic benefit per liter of water withdrawn or consumed as, say residential or industrial use. Maximizing economic benefit in these cases will likely suggest that water should be reallocated to other sectors. However, such a shift could cause significant social disruption or challenge the notion that agriculture has cultural or social benefits to a region beyond the economic value. This sort of conflict could even arise when considering favoring the allocation of water to one crop over another, purely because of economic efficiency. The question, then, is how to factor social impacts into the IWROM framework. Options for representing social impacts could include defining indicators of social capital, for example, employment associated with water use sectors. It may be possible to estimate the number of workers as function of water allocated to a given sector. For example, employment in agriculture is tied to crop types and acreages, which are tied to the amount of water allocated. In any case, stakeholders should be involved from the beginning in addressing this question of how to represent impacts associated with water-allocation strategies.

4 Conclusions

IWROMs use optimization methodologies to find the most efficient water-allocation strategies from an economic viewpoint, usually while considering the environmental impact of these strategies. Models of economic benefits associated with the consumption of water in various use sectors are derived and assembled in an objective function, including economic benefits associated with the environment. Hydrologic simulation models provide values of state variables, which are needed to evaluate the economic benefit models, constrain the physical system, and, in some cases, provide state variables for evaluating environmental impacts. The simultaneous evaluation and consideration of allocations across various water sectors, economic benefit models, models of the biophysical system, and economic and environmental impacts constitute the basis of the integrated nature of IWROMs.

IWROMs seek to find water-allocation strategies that occur in an efficient way, by maximizing the economic benefits or by minimizing the costs or number of people affected by such strategies. In addition, IWROMs allow for testing of different future scenarios that could be experienced by a particular region. These scenarios include potential changes in climate, land cover and land use, improvement of infrastructure, population, and consumer preferences. By testing these scenarios, the stakeholders can anticipate the potential environmental or economic consequences related to specific decisions taken in the basin.

IWROMs are particularly useful for regions where competition for water is intense, valuation of water for the various use sectors can be estimated, economic and operational impacts of proposed management alternatives are of interest, and data are available to calibrate supporting models. IWROMs allow for the simulation of and assessment of water resources economic policies and investments in water infrastructure. IWROMS seek to depict coupled human–nature relationships and mimic the impact of driving forces and feedbacks from the environment so they can effectively analyze sustainability. IWROMs support basin-wide decision-making since appropriate biophysical models can reflect spatial heterogeneity in hydro-climatic conditions and water uses among different subregions.

IWROMs have come a long way since their inception, but there are many challenges that need to be overcome. The hydrologic simulators employed in most IWROM applications have been relatively simple, which can limit the exploration of such issues as potential impacts caused by climate change or land cover modifications, groundwater sustainability, and water quality impacts associated with return flows. Assessment of model uncertainty associated with the hydrologic or the economic models should be exercised consistently, given that the parameters in these models are often poorly known at the present time and that IWROMs are often applied to examine future conditions, when the parameter values are usually even less certain. The inclusion of environmental flows and other relevant environmental factors through economic benefit functions has been somewhat unsophisticated to date. The importance of including social impacts related to shifts in water allocations among users should be considered; however, defining which social factors and how to quantify these factors will not be an easy task. Finally, it appears that including stakeholders in the development of IWROMs has not occurred. This situation could limit the interest of stakeholders in adopting new policies recommended by these models.

Even as IWROMs become more sophisticated, caution should be exercised when translating the results of IWROMs into policy. When it comes to water resource allocations, decision-makers should not concern themselves only with economic efficiency. First, it should be emphasized that quantitative approaches by their nature are reductive, and to be tractable, often will result in elimination of subtle relationships between sectors competing for water. Second, while it may be true that an integrated approach can help in resolving the ecological conflicts of economic activities, there are limits to this approach as only a weak integration of the economic and ecological aspects is feasible. The usual approach involves using economic values as a common denominator; however, these values have problems in reflecting the real ecological and social values of the resources. Third, there is a risk in fostering the notion of water as a commodity, because it shifts the public perception away from a sense of water as a common good, and from a shared duty and responsibility. A solution may seem simple and straightforward when designed on the basis of economic efficiency, but may, in the long run, be inequitable from a social perspective or unsustainable from an environmental perspective.

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Note

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