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Review

Hydro-economic models: Concepts, design, applications, and future prospects

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SUMMARY

Future water management will shift from building new water supply systems to better operating existing ones. The variation of water values in time and space will increasingly motivate efforts to address water scarcity and reduce water conflicts. Hydro-economic models represent spatially distributed water resource systems, infrastructure, management options and economic values in an integrated manner. In these tools water allocations and management are either driven by the economic value of water or economically evaluated to provide policy insights and reveal opportunities for better management. A central concept is that water demands are not fixed requirements but rather functions where quantities of water use at different times have varying total and marginal economic values. This paper reviews techniques to characterize the economic value of water use and include such values in mathematical models. We identify the key steps in model design and diverse problems, formulations, levels of integration, spatial and temporal scales, and solution techniques addressed and used by over 80 hydro-economic modeling efforts dating back 45-years from 23 countries. We list current limitations of the approach, suggest directions for future work, and recommend ways to improve policy relevance.

Contents

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Introduction

Recent decades have seen widespread use of systems analysis to help manage water resources. Systems analysis applied to water resources uses simulation and optimization models to explore the benefits of managing environmental systems as interdependent integrated units. Since the earliest applications of systems analysis to water resources, economic objectives and constraints have been common (Maass et al., 1962; Loucks et al., 1981).

Origins of the field

Economics and engineering are kindred disciplines which have frequently exchanged fundamental ideas over their long history (Lund et al., 2006). Modern engineering and economics share common ancestors in the French engineering schools of the 1800s (Hayek, 1950; Langins, 2004). A striking example is the fundamental economic concept of consumer surplus (section "Efficient water allocation") introduced by the French engineer Jules Dupuit (Dupuit, 1844; Ekelund and Hebert, 1999). This contribution and others were part of an effort to design civil infrastructure that would best serve society. Dupuit recognized the need to consider construction and operating costs; as well as the economic benefits of proposed public hydraulic works and operating schemes.

Water engineers continued to incorporate economic principles throughout the 19th and 20th centuries, increasingly in a system's analysis context. Often, optimization provided the mathematical link between economics and engineering. Economic engineering in the water field emphasizes the use of economic principles to support decision making, flexible and integrated management, benefit valuation, plan design, alternative evaluation, finance, and institutional design (Griffin, 1998; Braden, 2000; Lund et al., 2006). One manifestation of this mutually beneficial collaboration was the development of hydro-economic models.

Hydro-economic modeling can be traced to the 1960s and 1970s in arid regions such as Israel and the south-western United States. Early use of economic water demand curves to optimize a water resources systems were made by Jacob Bear, Oded Levin and colleagues (1964, 1966, 1967, 1970), Rogers and Smith (1970), and Gisser and Mercado (1972, 1973). Bear et al. established the conceptual framework (Gisser and Mercado, 1973; Noel et al., 1980) for regional-scale integrated water management models where water is allocated and managed to maximize net benefits derived from economic water demand curves. Since then researchers have used different names to refer to applications and extensions of this hydrologic engineering – economic water modeling approach including: hydrologic–economic (Gisser and Mercado, 1972), hydroeconomic (Noel and Howitt, 1982), economic–hydrologic–agronomic (Lefkoff and Gorelick, 1990b), institutional (Booker and Young, 1994), integrated hydrologic–economic-institutional (Booker, 1995), integrated river basin optimization (Ward and Lynch, 1996), efficient allocation (Diaz and Brown, 1997), integrated economic–hydrologic (McKinney et al., 1999; Rosegrant et al., 2000), economic-engineering (Newlin et al., 2002; Draper et al., 2003; Lund et al., 2006), integrated hydrologic–agronomic–economic (Cai et al., 2003a), demand and supply (Griffin, 2006), integrated hydrologic–economic (Cai et al., 2003a; Ringler et al., 2004; Pulido-Velazquez et al., 2006), holistic water resources–economic (Cai and Wang, 2006; Cai, 2008), integrated hydrodynamic–economic (Jonkman et al., 2008), and integrated ecological–economic (Volk et al., 2008). This review uses 'hydroeconomic' (Noel and Howitt, 1982) hereafter for brevity.

Hydroeconomic models: features and purpose

Hydroeconomic models represent regional scale hydrologic, engineering, environmental and economic aspects of water resources systems within a coherent framework. The idea is to operationalize economic concepts by including them at the heart of water resource management models. These models have emerged as a privileged tool for conducting integrated water resources management (IWRM) (Global Water Partnership, 2000; Mariño and Simonovic, 2001; Cardwell et al., 2006). Hydroeconomic models are solution-oriented tools for discovering new strategies to advance efficiency and transparency in water use. The goal is to look at a system in a fresh way to investigate promising water management schemes and policy insights. Recent hydroeconomic modeling research has been described by McKinney et al. (1999), Jakeman and Letcher (2003), Lund et al. (2006), Heinz et al. (2007), Cai (2008), Pulido-Velazquez et al. (in press), Brouwer and Hofkes (2008) and Ward (2009).

Engineers traditionally evaluate costs of building, operating and maintaining water supply, conveyance, storage, sewerage, drainage, and waste-water reuse infrastructure and estimate water requirements. In non-economic system models, water demands are commonly represented by fixed water "requirements" or delivery targets. The profession has often relied on a static view of water demands which can lead to over-design of infrastructure, waste, and slow adaptation to new conditions. In a mature water economy (Randall, 1981) with rapidly rising incremental costs of new supplies (aquifers already heavily exploited, best dam locations taken and other rivers protected) and increased conflicts among water users, a wider view is needed to face water scarcity problems. Economics helps water managers move from a static view of water demand, defined through water rights, priorities and projections of population growth and agricultural and industrial water requirements to a view of demand related to the economic concept of *value*. Water value changes with the quantity and type of use. Monetizing all water uses allows for an even-handed comparison among uses. Identifying the value of contested resources helps diffuse conflicts by introducing clarity and revealing the often relatively modest sums involved (Fisher et al., 2002). Monetization converts a complex multiobjective management problem into a simpler single-objective problem.

Hydroeconomic models differ from related tools such as engineering models that minimize financial costs or economic models such as dynamic optimization of groundwater stocks, economy-wide general equilibrium models, input–output analysis, cost-ben-

efit analysis, agent-based models, etc. In hydroeconomic models, water allocation is driven or evaluated by the economic values it generates. Hydroeconomic models represent all major spatially distributed hydrologic and engineering parts of the system. Representations include water balance components such as river flows, evaporation from surface water bodies, natural groundwater recharge and discharge, and return flows. Relevant water supply infrastructure and operations may include canals, reservoirs, desalination plants, water and waste-water treatment plants, groundwater or pipeline pumping stations, artificial recharge basins and other groundwater banking infrastructure. These hydrologic and engineering features are included in a node-link network, where economic demands have locations (nodes) and costs (or benefits) are incurred on links. The network accommodates both physical and economic spatially distributed systems, and integrates all hydroeconomic model elements.

Including economic water demands in addition to costs/benefits distinguishes hydroeconomic models from purely engineering models that maximize profit (e.g. hydropower operation) or minimize capital and/or operating costs.

Economy-wide economic models, such as general equilibrium or input–output models differ from most hydroeconomic models by representing how water resource policies or shocks affect the entire economic system, rather than focusing only on how economics affects water resource management. Typically these models do not represent spatially distributed water resource systems (e.g. Mukherjee, 1996) and so are not described here. Recently however, Jonkman et al. (2008) estimate both direct (flood damages) and indirect (economy-wide) costs of a major flood in the Netherlands by combining a hydro-dynamic model with an input–output economic damage model.

Agent-based models imbed social relations and information provision into economic and hydrological representations of water resource systems. This promising and related field is distinct from hydroeconomic modeling which focuses on combining neoclassical economics with hydrologic and engineering models. Agent-based models attempt to simulate human cognition and actions, particularly actions in response to other's actions and exogenous environmental variables. More realistic incorporation of learning and individual and collective action may benefit water management models by better representing conflicts, institutions and non-economic motivations. However, like other interdisciplinary modeling efforts (hydroeconomics included), there is a risk to produce complex tools that are too divorced from the simpler disciplinary approaches used by practitioners.

Why an economic approach?

Due to the life-sustaining qualities of water for humans and the environment, some commentators object to the use of economics to manage water. However, human access to clean water for basic needs and sufficient environmental and public use allocation are compatible with and encouraged by an economic approach to water management (Young, 2005, p. 8).

When basic human water needs are small compared to amounts used by other sectors, water should not be managed solely for drinking water needs. If demand exceeds supply in a mature water economy the relevant concept is water scarcity, not water shortage. When water is a scarce resource, it should be managed and allocated efficiently, i.e. to maximize the value it provides society. Managing any resource efficiently ("Pareto efficiency") occurs when a water allocation can provide no further gains in production or satisfaction without simultaneously creating a loss. Griffin (2006, p. 50) further distinguishes between neutral (Pareto front) and aggregate efficiency (maximize net benefits irrespective of distribution) to enable social preferences such as equity to be explicitly incorporated in the efficiency objective. Economics offers methods to evaluate and foster both equity and efficiency.

Besides health-sustaining human consumption and some non-economic values, water has value as: a commodity and input into various in-stream and off-stream production processes, as diluter and transporter of waste, recreational space, and ecological habitat (Young, 2005, p. 6). Representing these interests using a common monetary unit whenever possible establishes a framework for evaluating the trade-offs and synergies among competing water uses.

Using economic tools is not tantamount to advocating water markets (Chong and Sunding, 2006) as the mechanism to allocate all water resources; nor does it assume privatization. Constraints on allocations and flows are readily included in hydroeconomic models to represent political and cultural norms. Environmental demands can be valued or alternatively specified as constraints if their economic value proves too difficult or controversial to estimate. Further, hydroeconomic models are restricted in their ability to represent some practical aspects of markets such as transaction costs and agent behavior (Griffin, 2006).

According to the 1992 UN Dublin statement, "Managing water as an economic good is an important way of achieving efficient and equitable use, and of encouraging conservation and protection of water resources" (U.N., 1992). Under conditions of water scarcity an economic focus helps identify efficient water allocations and reduce wasteful practices. Water is typically allocated according to historical, institutional, political, legal, and social traditions and conditions. This division of water resources can be slow to adapt to environmental or water demand changes. Economic techniques help to allocate scarce resources and identify appropriate trade-offs between resource uses that reflect the values and choices of society.

Economic concepts for water valuation and allocation

Economics applied to water management has a long and distinguished history. Some basic concepts integral to understanding hydroeconomic models are described below. Several recent introductory textbooks provide accessible but in depth coverage of the economics of water resources (Gibbons (1986), Tsur et al. (2004), Young (2005), Fisher et al. (2005) and Griffin (2006)).

Efficient water allocation

A key concept for efficient water allocation is that water use values and costs vary with quantities rather than being fixed. Water is more valuable in a drought than in a wet period, and supply costs increase disproportionally when increasing output if all

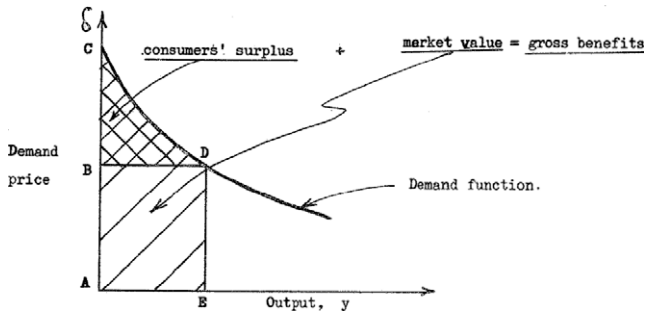

Fig. 1. Demand function consisting of the price (willingness to pay) for water at different quantities. Note that for a small quantity of water ("Output", *y*), the price is high (C). (Bear et al., 1964). N.B. market value alternatively named producer surplus.

major water sources are already exploited. Many traditional water planning practices assume fixed water use targets and operations, independent of prices and costs.

A demand curve (Fig. 1) for water presents consumer's willingness to pay for varying quantities of water. The *y*-axis is unit price or marginal willingness to pay, the *x*-axis is the quantity available. Due to a quirk of economic history, water demands are, counterintuitively, defined as the quantity demanded (*x*-axis) being a function of the price (*y*-axis). A steeper demand curve implies water use is less responsive to price changes (low price-elasticity) and user's value for water use is very sensitive to water availability. Demand curves are essential for economic analysis; "Determining economic value and production costs of water" discusses how they are estimated for various water uses. Because demand for water may change with location, type of water use (e.g. agricultural, municipal, industrial), hydrologic condition (e.g. dry year, normal year, wet year), or external influences (e.g. recession), hydroeconomic models may use more than one demand curve in one model. Fig. 1 shows how the area under a demand curve quantifies market value (ABDE) and consumer surplus (BCD), the sum of which are the gross benefits from a water delivery.

Integrating the demand curve quantifies the gross economic benefits derived from water allocation (see Fig. 2b). In this way demand functions can be used to allocate water to sectors that use it most productively. The optimal economic water allocation maximizes the aggregated net economic benefit (value) of water use in the system. The objective function can equivalently be formulated as a cost-minimization problem in which the costs modeled include water use benefits forgone (i.e. scarcity costs) and operating costs (e.g. Draper et al., 2003).

Maximizing net benefits is often equivalent to reallocating water until marginal net benefits are equal among all uses. The concept of marginality is central in economics to express the benefit or cost of one additional resource unit ("at the margin"). The microeconomic equimarginal principle states that in an optimal allocation among sectors, each sector derives the same utility from the last unit of resource allocated. In practice the equimarginal principal often does not hold at all time periods and locations within the hydroeconomic network because of non-economic constraints (e.g. hydrologic, engineering, institutional,...) (Cai, 2008) and the limited ability to respond to dynamic conditions.

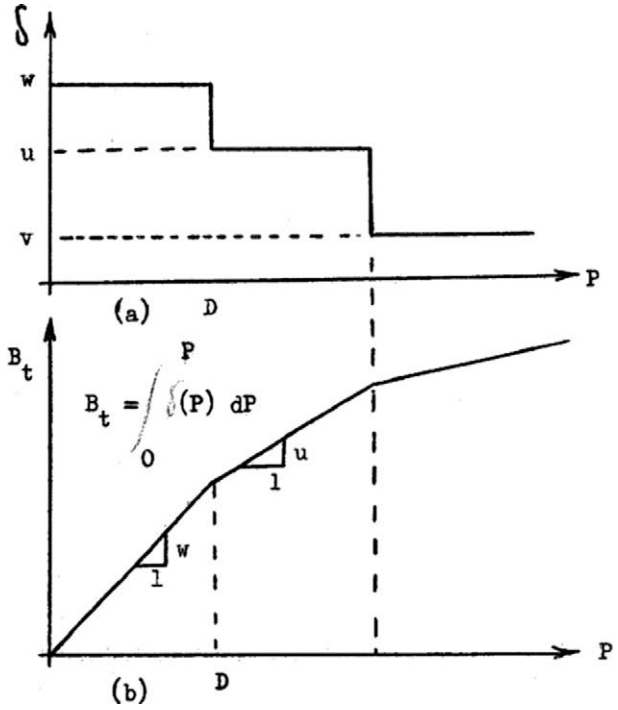

Fig. 2. Describes the relationship between the demand curve (a) and gross economic benefits (b). B_t are gross benefits, P is water quantity, δ is willingness to pay. Note that the demand "curve" in (a) is a step function made from two data points. When this step function is integrated, (b) is piece-wise linear. (Adapted from Bear et al., 1964). If the demand curve in Fig. 1 were integrated, the economic benefit function would be smooth. In both cases benefits exhibit diminishing marginal returns (rate of benefits decreases as water quantity increases).

Determining economic value and production costs of water

The prices for water in well-functioning water markets would offer an opportunity to directly observe water's economic value. Because markets are usually absent or inefficient, it is often necessary to estimate economic value of water using alternative approaches (Young, 2005). Valuation approaches and results depend on which specific water services are being valued, as well as where and why the valuation is being conducted. Water valuation can occur from a supply or demand perspective, resulting in a supply curve or a demand curve for water. For many water managers, the economic value of water evokes the capital (investment) and operating costs of supplying water that result in a supply cost curve. These tangible costs are typically calculated by engineering economists or accountants and are often simplified as being constant with respect to amount supplied (Griffin, 2006, chapter 10).

Economics contributes most to valuation from the water demand perspective where simpler methods are unusable. Gibbons (1986) provides a good primer. Valuation is done differently depending on whether water is considered an intermediate or a final good. When water is an input to a production process, such as in irrigation, hydropower generation and commercial or industrial uses, water demand is derived from the demand for the final output and the production function. In these cases water is an "intermediate good" and its demand is referred to as a derived demand. Residential or recreational water use are typically viewed as final demands in regional management modeling. These differences have important implications for valuation method selection, since different economic theories (of consumer's and producer's demands) are applicable to each case (Hanemann, 1998). When water is a final good, water provides direct utility to consumers willing to pay a specific amount of money for it. For intermediate goods (derived demand), water demand will be influenced by the technology producing the final goods and demand for the final output. In this case, estimating the economic value of water is equivalent to isolating the marginal contribution of water to the total output value (residual value).

Two broad approaches are available to model water demand: inductive and deductive valuation techniques (Kindler and Russell, 1984). Inductive techniques rely on econometric or statistical analysis of observed data to estimate price-response. This empirically-based technique is considered a 'positive' form of analysis. Deductive techniques usually use mathematical programming (optimization), although general equilibrium models and residual value methods also fall in this category (Tsur et al., 2004). Assuming optimal actions subject to economic and physical constraints is a normative approach which has prompted more "positive" variations (Howitt, 1995). In general econometric methods are data-intensive while optimization models are computationally-intensive.

Urban water demands

Since Howe and Linaweaver (1967) econometric approaches to estimate price-response and marginal benefits for the consumer dominate the literature (Arbues et al., 2003). Most use cross-sectional data, but also time series and panel data. The discussions have focused on which variables to include in the model in addi-

tion to water quantity and price, the best functional forms for statistical estimation, data, and magnitudes of the estimated price and income elasticities (Martin and Thomas, 1986; Dalhuisen et al., 2003). The main challenge to econometric estimations of water price-elasticity is the simultaneity problem posed by block-rate schedules, the level of disaggregation, dataset size, and the price specification (Young, 2005). Typical econometric applications include specifying a marginal price variable, a Taylor–Nordin difference variable, demographics, and climate data as regressors for water use (Griffin and Chang, 1991). Estimates of price-elasticity of water demand range from zero to almost two in absolute value (Espey et al., 1997; Dalhuisen et al., 2003). Price elasticity is the percent change in consumption per percent change in price.

Several indirect methods have been proposed to estimate economic costs of urban water scarcity based on optimization models that select the least-cost mix of residential water-saving techniques (Lund, 1995; Alcubilla and Lund, 2006; Rosenberg et al., 2007) or through contingent valuation surveys of willingness to pay (WTP) to avoid shortages (Griffin and Mjelde, 2000). Given lack of data, an easy form to characterize the residential demand curve within hydroeconomic models is the "point-expansion method". This method uses the data on observed price and water demanded at that price, a seasonal estimate of the long-run price-elasticity of that demand, then calibrates the parameters for a two parameter functional form by solving the resulting two identities. Constant price-elasticity forms are common in water management models that include the computation of consumer surplus (Griffin, 1990; Jenkins et al., 2003).

Agricultural water demands

Irrigation is by far the largest human consumptive use. Literature abounds on how to derive agriculture water demand curves and price-elasticities (Tsur et al., 2004; Young, 2005). Average and median values for price-elasticities for irrigation water fall in the inelastic range (Scheierling et al., 2006). Irrigation water demands are derived demands, since water is a production process input. Information on agricultural productivity can be used to construct crop-water production functions, from which the marginal physical product (first partial derivative of the production function with respect to the water input) can be derived for different water quantities. Finally, the marginal value (the demand curve) can be obtained from multiplying marginal physical productivities by crop prices.

Crop-water production functions represent the relation between water use and crop output, for particular agrobiologic and climatic conditions. This relation can be derived from controlled field experiments, from econometric methods (Moore et al., 1994), or by agronomic simulation models that yield the response of the crops to water applied under specific agronomic and climatic conditions (Dinar and Letey, 1996). Optimization models can be an alternative to data-intensive econometric methods. Howitt (1995) combines regional equilibrium models and positive mathematical programming (PMP) to calibrate flexible crop production functions.

Irrigation water demands depend on farmers decisions' on crop mix and timing, water application, and irrigation technology. Many factors affect farmer's decision on crop mix (crop selling price, input costs, water availability and water price, agro-climatic characteristics, and risk and management effort involved). An extensive literature on mathematical programming models tries to reproduce farmer's decisions at the farm or irrigation district level. Most maximize profit or gross revenue. PMP models calibrate these optimization models to reproduce observed farmer decisions.

Irrigation water demands are usually represented in hydroeconomic models using piece-wise linear or quadratic equations, exogenously generated, relating water application to economic benefits. In some cases, complex crop yield functions are explicitly included in the model (Cai et al., 2003b).

Hydropower and industrial water demands

The benefits of hydropower production are often defined using the alternative cost technique, calculating the cost savings of hydropower compared with the next less expensive energy production alternative (Gibbons, 1986; Booker and Young, 1994). Benefit functions also can be derived from the quantity of energy produced and its energy market price. The energy produced depends on the powerplant discharge, the hydraulic head and the efficiency of the turbine-generator group. Hydraulic head is often represented as a linear function of reservoir storage (Diaz et al., 2000; Cai et al., 2003a) although this can produce inaccuracies. Economic valuation of hydropower has become more complex due to energy market deregulation and decentralization, and the rise of contracted firm energy commitments and random purchases on the spot market.

As with commercial urban uses, elasticity of demand for industrial uses varies among types of industries (reviewed by Renzetti, 2002). Jenkins et al. (2001, 2003) characterize the industrial demand using a linear production loss function defined by the current consumption and data from a survey on the economic value of production lost if water deliveries were cut back by 30% (CUWA, 1991).

Environmental and recreational water demands

In-stream values for recreation and wildlife can be comparable to more traditional economic use values (Colby, 1990). Approaches for quantifying benefits of environmental water uses either infer WTP from observations of actual expenditure choices of the consumers (e.g. travel cost method or hedonic pricing) or use surveys to ask consumers about the values they place on environmental services (contingent valuation) (Freeman, 2003; Young, 2005). Benefit transfer approaches adapt results from studies at other sites (Brouwer, 2000). Despite the advances in methods and applications, environmental valuation is still an "imperfect art", subject to interpretation and debate (Braden, 2000; Shabman and Stephenson, 2000). Finally, shadow values on minimum flow constraints in hydroeconomic models provide the opportunity cost of environmental water, an indirect form of supply-side valuation (Medellín-Azuara et al., 2007).

Production costs

Water production costs include variable costs to pump, treat, and improve water quality as well as capital and fixed costs for infrastructure and operations. Most hydroeconomic models are designed for management, and so they include only variable operating costs of existing infrastructure. For linear and non-linear programming, variable costs must be convex (as they often are in practice due to decreasing returns to scale) to guarantee identifying a globally optimal solution.

For capacity expansion planning, fixed and capital costs should also be considered. However, fixed and capital costs are often non-convex due to discontinuous and decreasing marginal facility costs. This inhibits use of linear and non-linear programming, which is why fixed and capital costs are often ignored. There are several ways to include these costs. First, capacity expansion decisions can be considered as a side calculation outside the optimization process (comparing capital costs to benefits from separate optimization runs, one with and one without the infrastructure in place) (Fisher et al., 2005). Alternatively, capital costs are annualized (using the discount rate and estimated project lifetime) and then added to the operating costs. Third, capacity expansions are included as separate linear, integer, or binary decisions with additional constraints added to ensure operational decisions within

existing and expanded capacity limits (e.g. Rosenberg et al., 2008). Non-convex costs (for minimization problems, or non-concave costs for maximization problems) require using dynamic programming or heuristic search techniques to identify an optimal or nearly optimal solution.

Hydroeconomic model design and implementation

Many choices face the modeler when designing the mathematical formulation and choosing a solution algorithm. General rules and good practices of environmental modeling apply here as well (Jakeman et al., 2006). An essential feature is to design a model capable of answering questions and providing insights for resource managers, stakeholders and policy makers. Model design affects data requirements, available solution methods, and the types of results obtainable.

Model components

Most hydroeconomic models share basic components including hydrologic flows, water management infrastructure, economic water demands, operating costs, and operating rules. Since Maass et al. (1962), water resource systems have been modeled as networks of storage and junction nodes joined by conveyance links representing river reaches, canals, pipelines, etc. Water demands and consumption, and other features where water incurs a cost or benefit also are represented as nodes. The network format is straightforward, efficient and parsimonious for both simulation and optimization models. Boundary conditions in the form of inflows, outflows or other fixed flows can occur anywhere in the network.

Hydrologic flows entering and leaving the modeled domain and relevant internal inflows must be estimated. These include external surface or subsurface inflows and local precipitation-driven fluxes such as runoff and aquifer recharge. For operating purposes short-term forecasts of inflows based on operational weather predictions and current hydrologic conditions can be used. External system inflow data may come from historical flow gage records or synthetic time series generated by stochastic hydrology models. Alternative hydrologic scenarios, for example from downscaled global circulation models representing climate changes, may also be used. When historical data do not exist, calibrated hydrologic models can fill the gap. Hydrologic models are the main source for ungaged flows such as groundwater recharge, evaporation and local runoff.

Water management infrastructure consists of natural and built facilities to store, convey, treat, and use water such as river reaches, canals, pipelines, reservoirs, aquifers, pumps, powerhouses, treatment plants, groundwater injection wells, recharge basins, and water demand intake locations. Minimum and maximum capacities and operating costs are specified for each element. Using data and network topology from existing models is a quick and credible way to build a hydroeconomic model. Simulation models calibrated and maintained by water management institutions are an ideal foundation for more abstract management models.

Economic water demands can be represented by functions providing gross economic benefits generated during a particular model time-step (Bear et al., 1964). If the model's objective is cost minimization, water scarcity costs incurred by lower deliveries can be represented by penalty functions (Newlin et al., 2002). Environmental water uses may be alternatively represented with operating rules or constraints, where an objective function valuation is unavailable.

Operating costs include pumping, treatment, artificial recharge and other costs to move water between network nodes. They also can include negative costs (benefits) from hydropower generation. Water quality costs to urban users can be represented as operating costs, so they could be assessed and varied depending on the

Table 1
Some design choices, options, and implications for building a hydroeconomic model.

Options	Summary	Advantages	Limitations
Simulation/optimization			
Simulation	Time-marching, rule-based algorithms; Answers question: "what if?"	Conceptually simple; existing simulation models can be used, reproduces complexity and rules of real systems	Model only investigates simulated scenarios, requires trial and error to search for the best solution over wide feasibility region
Optimization	Maximizes/minimizes an objective subject to constraints*; answers question: "what is best?"	Optimal solutions can recommend system improvements; reveals what areas of decision space promising for detailed simulation	Economic objectives require economic valuation of water uses; ideal solutions often assume perfect knowledge, central planning or complete institutional flexibility
Representing time			
Deterministic time series	Model inputs and decision variables are time series, historical or synthetically generated	Conceptually simple: easy to compare with time series of historical data or simulated results	Inputs may not represent future conditions; limited representation of hydrologic uncertainty (system performance obtained just for a single sequence of events)
Stochastic and multi-stage stochastic	Probability distributions of model parameters or inputs; use of multiple input sequences ('Monte-Carlo' when equiprobable sequences, or 'ensemble approach' if weighted	Accounts for stochasticity inherent in real systems	Probability distributions must be estimated, synthetic time series generated; presentation of results more difficult; difficulties reproducing persistence (Hurst phenomenon) and non-stationarity of time series
Dynamic optimization	Inter-temporal substitution represented	Considers the time varying aspect of value; helps address sustainability issues	Requires optimal control or dynamic programming
Submodel integration			
Modular	Components of final model developed and run separately	Easier to develop, calibrate and solve individual models	Each model must be updated and run separately; difficult to connect models with different scales
Holistic	All components housed in a single model	Easier to represent causal relationships and interdependencies and perform scenario analyses	Must solve all models at once; increased complexity of holistic model requires simpler model components

* If optimized time-horizon is a single time period, the model can be considered a simulation model that uses an optimization computational engine.

source of water delivered to each urban area, where incoming water quality varied primarily with source (Draper et al., 2003).

Choices of model formulation and design

Table 1 lists several model design choices and options hydroeconomic modelers must make to built a model. Further discussion on some of these choices follows.

Simulation or optimization?

Simulation and optimization answer different questions ('what if' and 'what is best', respectively) and can be used separately or together. Models that simulate decisions on a time-step by time-step basis can more realistically represent complex systems with non-linear physical or institutional processes. Models focusing on detailed local decisions (e.g. farm level) often find simulation useful (Bredehoeft and Young, 1970; Young and Bredehoeft, 1972; De Ridder and Erez, 1977; O'mara and Duloy, 1984; Brown et al., 1990; Letcher et al., 2004; Brown and Rogers, 2006; Marques et al., 2006). Economic evaluation of simulated alternatives can provide insights on benefits and inefficiencies of design or management policy without driving water allocation and operations.

Optimization formulates problems using a mathematically stated objective subject to equations that represent physical and management constraints of the system. Multi-period optimization links more than one time period in a single model. This helps capture the trade-offs of resource allocation over time such as storage in reservoirs and aquifers but may quickly yield large-models with non-linearity and perfect foresight of inflows. Optimization objective functions typically maximize expected net benefits (expected value of gross benefits derived from water use minus costs) or similarly minimize costs such as water scarcity costs, capital costs of investments, and operating costs. Optimization models can be solved analytically, with mathematical programming, dynamic optimization, or heuristic (global) search techniques such as evolutionary algorithms or combinations of the above.

Because optimization's relevance in economic theory, hydroeconomic models commonly use optimization computation engines regardless of whether they are built for simulation or optimization. When optimization is used to simulate (e.g. Labadie and Baldo, 2000; Draper et al., 2004; Marques et al., 2006; Reynaud and Leenhardt, 2008), each time period is a separate optimization problem, with results at $t-1$ serving as boundary conditions for the model during period t. Simulation models can reproduce actual operating rules without benefiting from the perfect hydrologic foresight of multi-period optimization. For example, simulated reservoir releases are based on existing storage without anticipation of future inflows. Operating rules codify operational, legal and institutional regulations. They allow simulation models to replicate water allocation decisions in accordance with existing water management practices. Optimization models follow an objective rather than a set of rules that are not directly implementable, such as "maximizing regional net benefits". In this case accurate water valuation is essential as the water allocation benefit functions guide the solution. The purpose of deliberately simplifying or partially by-passing existing operating rules is to better explore the physical and economic potential of the system in order to propose policy insights and improvements. Simulation and optimization perform well together, using optimization to identify promising solution strategies and simulation models to test and refine these in more detail (Loucks et al., 1981).

Representing time

Deterministic models consider a single-set of fixed boundary conditions (e.g. flows and demands) and results. Deterministic models become probabilistic when run many times with different inputs and report results spanning a broad range of conditions (e.g. Monte-Carlo simulation, implicit-stochastic optimization) (Labadie, 2004).

Stochastic models explicitly consider the probabilistic nature of model inputs and parameters. Results take the form of probability distributions or processes rather than single numbers. Explicitly stochastic methods are common in pure engineering or pure economic models but still relatively rare in hydroeconomic applications (Reca et al., 2001b; Houk et al., 2007; Rosenberg et al., 2008; Tilmant et al., 2008). Hydroeconomic models tend to implement variations of deterministic optimization where results are time series of optimal allocation operations (e.g. storages and flows).

If discounting is used in the objective function to account for opportunity costs (the 'time-value of money'), a discount factor, $(1+i)^{-t}$ where i is a discount rate, multiplies future benefits and costs of the objective function (evaluation function in simulation). Models that maximize present value of net benefits or net annualized benefits are commonly solved using linear or non-linear mathematical programming (optimization). Dynamic (time-varying) economic optimization models using dynamic programming or optimal control consider inter-temporal substitution of resources rather than only present value (Conrad and Clark, 1987). If no economic consideration is explicitly given to time in the form of an equation of motion for the state variables, the model is referred to as static.

Submodel integration

Integration refers to how different submodels interact and the breadth of processes and decisions represented together. Holistic models endogenously (internally) calculate all inputs and outputs within a single model. A modular design connects independent submodels, without having them interacting within a single program. Braat and Lierop (1987) describe these, respectively, as holistic or compartment approaches, a terminology adopted by Cai et al. (2003a), Cai (2008) and Brouwer and Hofkes (2008). The main question is whether to solve the economic model endogenously within the water management model or to estimate water demands with an external economic model. The advantages of modularity include increased probability of convergence on an optimal solution, the ability to go into more detail in each sub-field, and the ability to be independently updated and developed. Holistic models can more effectively represent causal relationships and interdependencies. Scenario-based studies such as climate change impact studies, are easier to execute with holistic models since they do not require representing the changed policies or conditions separately for each submodel. An example of a modular approach is Draper et al. (2003) where economic scarcity cost curves are determined by a exogenous economic model (Howitt et al., 2001). A holistic approach is presented by Cai et al. (2003a) where water demand curves are estimated endogenously. However, few models are fully 'holistic'; a seemingly holistic hydroeconomic model that does not represent rainfall-runoff processes would be considered modular in the context of a climate change impact study. Economy-wide economic models, such as general equilibrium or input–output models that represent spatial hydrology (e.g. Jonkman et al., 2008), are also holistic hydroeconomic models. They have wider breath, including how water resource policies or shocks affect the entire economic system, rather than focusing only on how economics effects water resource management.

Whether in a single or in separate models, the question remains of which model components to include and at what scale. A wide range of both hydrologic and engineered water supply processes and options can be represented. More or less detailed surface water, groundwater flow and stream-aquifer models can be embedded, drastically affecting run times and the scale at which

management inferences can be made (Harou and Lund, 2008). Water quality is rarely explicitly modeled in hydroeconomic models because of the added complexity and computational cost and the difficulty of quantitatively assessing economic effects; recent exceptions include Bateman et al. (2006) and Volk et al. (2008). Constraints or additional costs for some water sources can be used to implicitly represent water quality. Besides water resource and economic components, other submodels that may be relevant in a given context include agronomic and ecological submodels.

Modeling scales

Modeling scale is a critical subject encompassing spatial and temporal domain and discretization (Jakeman and Letcher, 2003). The domain describes the boundaries of the model. Spatial domains range from a single farm or household to groups of countries while the temporal domain is the model's time-horizon; often a year or more. Discretization describes the subdivision of the spatial and temporal modeled domains. The spatial domain is to be separated into subdomains (e.g. grid cells, sub-basins) while the temporal domain is subdivided into time-steps. Scale determines what issues and questions the model will be able to address.

The most common spatial domain considered in hydroeconomic modeling is regional although analysis can be useful from household to international scales. If the focus is on water demand management and conservation, household or utility-level models can help identify optimal investments at the household and water utility scales (Alcubilla and Lund, 2006; Rosenberg et al., 2007). Management at the utility scale can benefit from investigating pricing, infrastructure investment and operations and maintenance policies (Wilchfort and Lund, 1997; Jenkins and Lund, 2000). Using river basin boundaries to delimit model domain is especially appropriate when such boundaries also define the jurisdiction of water agencies. Hydroeconomic models have also been applied to transboundary river basin conflicts (e.g. Fisher et al., 2002; Ringler et al., 2004).

Discretization relates how the spatio-temporal domain is subdivided. Spatially the model can be lumped (spatial variability), semi-distributed (e.g. using lumped subbasins or subregions) or distributed (mesh overlays domain). Most economic models of natural resource use are spatially lumped; with some element of spatial distribution of processes and variables being the trade-mark of most hydroeconomic models. Semi-distributed is the most flexible and commonly used spatial discretization. In a typical application the water resource system is represented by a node-link network, with flows routed between nodes using simplified hydrologic equations (ranging from mass balance equations to hydrologic routing schemes). Distributed hydraulic models (e.g. using a regular 1, 2 or 3D mesh) are uncommon in hydroeconomic models as such detail is usually not relevant at the policy and planning levels. An exception is spatially discretized groundwater models, because of groundwater pumping costs and spatially dependent environmental effects (Pulido-Velazquez et al., 2006; Schoups et al., 2006b; Harou and Lund, 2008).

The semi-distributed approach brings the challenge of linking hydrologic and water supply infrastructure to areas where economic water demand or production is homogenous enough to be modeled as a unit (Cai, 2008). The node-link structure is well-suited to link different scales; network connectivity can usually be represented concisely in a single connectivity matrix (Labadie, 2004). While choosing a water resource scale will strongly effect what equations are used to model water resources, economic formulations tend to vary less across different scales.

Temporal domains range from a few days for operational models to decades for planning applications. Few hydroeconomic models explicitly consider the stochastic nature of inflows because of the impractical computation burden. Temporal discretization depends on the management questions of concern. Models focusing on short-term operations (e.g. flood control, hydropower) use small time-steps (daily or less) to model hydrologic and hydraulic processes such as flow routing. Maximizing net benefits from hydropower operations often requires a daily time-step or smaller. Operations models only represent groundwater when stream-aquifer fluxes are significant. When flow through the surface water system is faster than model time-step, flow routing in rivers is unnecessary and should be avoided. Models focusing on longer-term planning such as reservoir storage use weekly to annual time-steps and rarely require flow routing (except for flood operations). In this case, flows are instantaneous and modeled with a mass-conserving network. Here the focus is on long-term storage and allocation operations such as in conjunctive use of surface water and groundwater, drought management, or screening for infrastructure development.

Environmental and social goals

Another design choice is how to represent environmental or 'ecological' flows. Modelers can use environmental economic valuation techniques ("Environmental and recreational water demands") or treat environmental requirements as low-flow constraints (e.g. Jenkins et al., 2004). The latter approach is helpful when it is difficult or controversial to value environmental services. Other models use environmental and recreational economic value functions obtained using non-market valuation techniques, so that non-consumptive in-stream uses and consumptive uses compete for the allocation of water in the system (Ward and Lynch, 1996; Diaz et al., 2000).

Like ecological goals, social policies, institutional realities and political considerations can readily be included as constraints within hydroeconomic models (Fisher et al., 2002). Including these considerations is necessary if practitioners will use hydroeconomic models to help reduce rather than foment conflicts. For example hydroeconomic tools help evaluate the equity implications of different water policies since they estimate the redistribution of benefits and costs among affected parties (e.g. Draper et al., 2003). Evans et al. (2003) analyzed the trade-offs among the goals of efficiency, equity in water allocation, and equity in income distribution for an agricultural watershed. Cai et al. (2002) distinguished between temporal and spatial equity. Babel et al. (2005) allocate water according to maximize equity and net economic benefits. Ward and Pulido-Velazquez (2009) test a two-tiered water pricing system that sets a low price for basic needs, while charging full marginal cost for discretionary uses. Maneta et al. (submitted for publication) investigate effects of irrigation costs and water access on farmer incomes.

Social sustainability criteria are also readily incorporated into hydroeconomic models, by specifying appropriate constraints and/or low discount rates in the objective function. Although elusive to define, sustainability criteria try to provide sufficient resources for future generations to meet their future needs (Loucks, 2000). These criteria can be included in hydroeconomic models, for example by requiring storage at nodes to be the same at both the beginning and end of the period of analysis (Draper et al., 2003; Harou and Lund, 2008a). Alternatively, use or availability of particular groundwater or surface water sources can be restricted within pre-determined, sustainable, safe yields (e.g. Fisher et al., 2005).

Software implementation

Several software options are available to run hydroeconomic models. One solution is to implement custom (fully user defined) model formulations within generic modeling systems. Optimization modeling systems integrate model data, formulation, solution

and results definition. Commercial examples of such systems include GAMS, AMPL, AIMMS; all of which link model equations written in algebraic notation to commercial solvers implementing linear, integer or non-linear optimization. These systems are flexible, transparent, self-documenting, provide simple links between model formulation and solver solution, and therefore have seen early and widespread use by both economists and engineers to implement hydroeconomic models. A related approach is to access optimization solvers through spreadsheet programs. Simulation modeling systems (also called systems dynamics software) solve user-defined simulation models with a commercial solver engine. Although most modeling systems are generic, at least one is water specific. The Interactive Component Modeling System (ICMS) (Argent et al., 2006) was used to implement a hydroeconomic model called the Water Allocation Decision Support System (WAdss) (Letcher, 2005).

Custom models benefit from having a graphical user-interface and data management system to input, manage and display model inputs and outputs. The modeling systems described above facilitate building graphical user-interfaces to varying degrees. Other options include creating application-specific software or using a model platform. Application-specific software such as CALVIN (Draper et al., 2003) and WAS (Fisher et al., 2002; Rosenberg et al., 2008) are especially built to link a solver to a user-interface and database. Alternatively a model platform can link an existing custom model to a generic user-interface and data manager. HydroPlatform (Harou et al., 2009) is a geographically-based open-source model platform that works with existing hydroeconomic models built with modeling systems such as GAMS.

If a custom model formulation is not required a generalized water resource Decision Support System (DSS) can be used. A few hydroeconomic DSS exist such as MITSIM (Strzepek et al., 1989), AQUARIUS (Diaz and Brown, 1997; Brown et al., 2002), and AQUAPLAN (Tilmant et al., 2008). Other DSS may be configured to include hydroeconomic components. Examples include AQUATOOL (Andreu et al., 1996; Andreu-Álvarez et al., 2005; Pulido-Velazquez et al., in press), OASIS (Randall et al., 1997), MODSIM (Labadie and Baldo, 2000), MIKE BASIN (Jha and Das Gupta, 2003), CALSIM (Draper et al., 2004), WEAP (Yates et al., 2005), WSM DSS (Todini et al., 2006), and WaterWare (Cetinkaya et al., 2008).

Study design and results

A typical hydroeconomic modeling study involves a base case representing current infrastructure and water management practices. Reproducing historical results is important to establish model credibility. Further alternatives and scenarios may include new infrastructure, operating rules, institutional and policy changes, changes in demands or hydrologic conditions (e.g. climate change), or combinations of these. Users then compare and contrast results for the different alternative and scenarios.

Establishing a base case is related to model calibration, the process by which model input data, parameters, assumptions and process equations are tested and iteratively improved to better agree with observed results. Model calibration often is a lengthy process through which modelers learn about both the water system under consideration and about their model's assumptions, limitations and benefits (Draper et al., 2003). Partially automated calibration methods have been applied to optimization models (Howitt, 1998; Cai and Wang, 2006) based on the concept of PMP (Howitt, 1995).

Basic results of both simulation and multi-period deterministic optimization are overall economic performance and the time series of water system operations (e.g. reservoir releases, groundwater pumping, artificial recharge, etc.). For small systems, operation rule parameters can be solved for directly (Schoups et al., 2006a); for large systems they can be derived by statistically analyzing optimal operations (Lund and Ferreira, 1996). When optimization is used, marginal values (i.e. "value of one more unit") of water and infrastructure are a significant result from hydroeconomic models. These marginal values (named dual values, shadow values, Lagrange multipliers, or imputed prices) are produced by mathematical programs when a constraint limits the optimal solution. They indicate the change in the objective if the constraint were relaxed by one unit. Because hydroeconomic models are single-objective measured in monetary units, shadow values have direct economic significance. Hydroeconomic optimization models produce valuable information on marginal values of water, infrastructure and ecological flows. In a standard network formulation, shadow values on flow continuity constraint equations provide time series of the value of adding one unit of flow at any network junction. Shadow values on infrastructure capacity or low flow constraints provide the marginal values of expanding infrastructure bottlenecks or reveal the opportunity cost society pays to maintain low flow requirements (e.g. having an in-stream flow be 10 rather than 9 m^3/s), respectively. However, shadow values cannot represent the consequences of simultaneously changing multiple constraints.

These are just some examples of generic output. In reality, the range of outputs matches the breath of the diversity of reasons to build hydroeconomic models. A representative set of applications is described in the next section.

Applications

Hydroeconomic modeling applications in the literature cover a range of water resources problems, locations, and innovations (Table 2). Table 2 divides applications into seven permeable groups, described briefly here.

Applications for in-stream uses include hydropower, navigation and recreation. Off-stream uses are usually consumptive, e.g. irrigated agriculture or urban supply. To allocate water efficiently, in-stream flow values must be incorporated into the allocation process (Colby, 1990; Griffin and Hsu, 1993). However, environmental water uses, such as ecological minimum in-stream flows are usually not represented economically; no such applications were found. Endogenous agronomic models can be used to represent the effects of agricultural practices on water use and vice versa. Agricultural yield can be simulated given particular water applications, irrigation technology and water salinity levels.

Engineering infrastructure and capacity expansion are themes of engineering focused models that use economic criteria for evaluation. An advantage of optimization to analyze water supply infrastructure is that shadow values evaluate marginal value of capacity (Rogers and Smith, 1970).

When groundwater is managed conjunctively with the rest of the water resource system, hydroeconomic models can show the potential for groundwater banking (Pulido-Velazquez et al., 2004; Harou and Lund, 2008a). Models that represent groundwater pumping costs that vary with depth are non-linear (quadratic) since water levels will depend on volume pumped. Distributed-parameter groundwater models add spatial information which enable local relevance of model results, rather than broad regional trends.

Many papers investigate the benefits of flexible allocation through various types of water markets. Water markets are always regulated by institutions that impose constraints to protect against environmental degradation or secondary economic effects (externalities). Modeling various constrained markets can helps identify more effective and beneficial arrangements for the regional economy.

Water management models that consider economic criteria tend to contradict theories about looming regional or global water

Table 2
Selected hydroeconomic modeling applications grouped into categories. Many studies mentioned here could be placed under several application categories; one is chosen based on salient model features.

Major problem(s)	Location	Model features and innovations	Citation(s)
In-stream and off-stream intersectoral allocation and use			
Water scarcity, inefficient allocation of small flow increases	Hypothetical basin, Western USA	Allocation to hydropower of water obtained by vegetation removal	Brown et al. (1990), Diaz et al. (1992)
Exploiting synergies among non-consumptive uses	Rio Chama Basin, New Mexico, USA	Complementarities between river recreation, lake recreation, and hydropower	Ward and Lynch (1996,1997)
Preserving springs for recreation and ecological habitat	Edwards Aquifer, Texas, USA	Groundwater management for ecological habitat protection, water market investigated	McCarl et al. (1999)
Trade-offs between ecological and economic objectives	Border Rivers region, Queensland, Australia	Consequences of trade and allocation water for environmental use; minimizes differences between actual and natural flow regimes	Tisdell (2001)
Optimal drought allocation planning with agricultural demands	Irrigation District of Guadalquivir Basin, Spain	Principal component analysis used to generate stochastic variables for three hierarchical submodels: crop, irrigation district, basin	Reca et al. (2001a,b)
Competitive hydropower and agricultural demands	Vadielo Reservoir, Spain	Identifies economic gains of an inter-temporal trade agreement	Bielsa and Duarte (2001)
Agricultural, urban and environmental uses	Maipo basin, Chile	Return flows, considers hydrologic and economic efficiency	Rosegrant et al. (2000), Cai et al. (2003c), Cai (2008)
Over-allocated surface and groundwater supplies	Namoi Basin, Australia	Trade-offs from water allocation policies; integrated assessment	Letcher et al. (2004)
Allocation between sectors with disparate economic returns	Nong Pla Lai Reservoir, Thailand	Multi-objective equity and net economic benefit maximization	Babel et al. (2005)
Distribution of dry-season flows between farmers, deforestation, erosion, surface water quality	Mae Chaem catchment, Thailand	Integrated modeling includes crop growth, erosion, rainfall-runoff, household decision, socio-economic impact models	Letcher et al. (2006)
Water shortages threaten endangered species habitat; least-cost source for ecological needs	Platte River Basin, Western USA	Least cost water supplies from agriculture identified to reduce environmental water shortages; Stochastic agricultural crop mix model	Houk et al. (2007)
Operating cascades of reservoirs in a multi-objective, transboundary context	Euphrates basin (Turkey, Syria)	Stochastic programming to assess statistical distribution of marginal water values in multipurpose multireservoir system (hydropower, irrigation)	Tilmant and Kelman (2007), Tilmant et al. (2008)
High agricultural and urban summer demands; spatially heterogenous demands	Neste basin, France	Economic optimization driven simulation (agricultural, domestic, industrial users), scenarios: agronomic, climatic or economic	Reynaud and Leenhardt (2008)
Water supply, engineering infrastructure and capacity expansion			
Crop and water supply infrastructure for irrigation	Tista Project, East Pakistan	Interactions of surface water–groundwater system within economic irrigation context	Rogers and Smith (1970)
Water supply; desalination; sector allocations	San Luis Obispo County, California, USA	Mixed integer programming	Armstrong and Willis (1977)
Operating rule development	Missouri River, Columbia River, USA	Economic-based implicit-stochastic optimization	Lund and Ferreira (1996)
Agricultural and urban water supply; environmental uses	Statewide California, USA	Database management; large diversified system; flexible policies; infrastructure expansion	Draper et al. (2003), Jenkins et al. (2004), Null and Lund (2006)
Competing uses of infrastructure	Panama Canal System, Panama	Trade-off between navigation and hydropower, capacity expansion	Watkins and Moser (2006)
Probabilistic drought planning and operations	East-Bay Municipal Utility District, California, USA	Linked supply and demand spreadsheet models	Wilchfort and Lund (1997), Jenkins and Lund (2000)
Water conservation and infrastructure expansions with variable water availability	Jordan	Stochastic mixed integer programming with non-price water conservation programs and infrastructure expansions	Rosenberg et al. (2008)
Conjunctive use of groundwater and surface water			
Economic optimization of conjunctive use	San Joaquin River Valley, California, USA	Maximize expected net benefits from agricultural production; stochastic dynamic programming	Burt (1964)
Optimizing groundwater in an integrated system	Israel	Economic optimization of groundwater use with an integrated system using water demand curves	Bear et al. (1964), Bear and Levin (1966, 1970)
Stream-aquifer interaction, spatial hydrologic effects	Hypothetical and Platte Valley, Colorado, USA	Simulation of conjunctive use system with distributed groundwater simulation and economic model	Bredehoeft and Young (1970), Young and Bredehoeft (1972)
Regional economic and agricultural development plan considering stochastic supplies	Varamin Plain, Iran	Combines an agricultural production optimization model with a distributed groundwater simulation model and a node-link surface water network	De Ridder and Erez (1977)
Agricultural water allocation	Yolo County, California, USA	Integrated groundwater model using regression equations	Noel et al. (1980), Noel and Howitt (1982)
Efficient conjunctive use and irrigation supply system design	Indus Basin, Pakistan	Simulation of joint effect of water allocation and groundwater well tax or subsidies on economic efficiency	O'mara and Duloy (1984)
Groundwater-irrigated agriculture	Salinas Valley, California, USA	Effectiveness of basinwide groundwater management; recharge from ephemeral streams	Reichard (1987)
Economically optimal steady-state pumping	Madera County, California, USA	Approximating the optimal groundwater pumping for multi-aquifer stochastic conjunctive use	Provencher and Burt (1994)

Table 2 (*continued*)

Major problem(s)	Location	Model features and innovations	Citation(s)
Economically optimal pumping	Kern County, California, USA	Artificial recharge of groundwater	Knapp and Olson (1995)
Conjunctive use infrastructure and water banking	Southern California, USA	Optimization of groundwater conjunctive use and infrastructure	Pulido-Velazquez et al. (2004), Harou and Lund (2008a)
Increasing agricultural demand, seawater intrusion	Adra River Basin, Spain	Embedded multireservoir method stream-aquifer model, eigenvalue method groundwater model, NLP	Pulido-Velazquez et al. (2006)
Surface water costs cause groundwater overdraft	Tulare Basin, California, USA	Economically driven simulation; quantifies surface water price effect on groundwater	Marques et al. (2006)
Drought, coastal irrigated agriculture	Yaqui Valley, Sonora, Mexico	Embedded agronomic, distributed groundwater model; multiobjective interannual optimization for sustainability and spill control; derived conjunctive use rule	Schoups et al. (2006a,b)
Institutions, water markets and pricing			
Water scarcity due to lack of infrastructure	California, USA	Non-linear spatially distributed supply and demand functions, inequality between number of supply and demands functions	Vaux and Howitt (1984)
Stream-aquifer water rights issues	South Platte River, Colorado, USA	Quasi-market maximize regional income and protect senior river water rights	Young et al. (1986)
Scarce irrigation supplies; decreased agricultural productivity from salinity	Arkansas Valley, Colorado, USA	Market simulation of changes in surface and groundwater value due to salinity	Lefkoff and Gorelick (1990b,1990a)
Cost of new urban supply projects in south-western USA	Colorado River, USA	Market for consumptive uses, hydropower production, river salinity; six institutional alternatives tested	Booker and Young (1994)
Inefficient institutional constraints on water market	Lower Rio Grande Valley, Texas, USA	Institutional water market constraints; optimal portfolios of rights, options, and leases	Characklis et al. (1999,2006)
Water scarcity and demand for water imports	Southern California, USA	Economic benefit of flexible water allocation policies	Newlin et al. (2002)
Growing demand, opposition to new reservoirs, institutional limits on transfers	Kern County, California, USA	Dynamic optimization of markets and inter-temporal groundwater management	Knapp et al. (2003)
Aquifer depletion and environmental damage	State of Tamil Nadu, India	Adaptive groundwater pricing with price as function of groundwater levels and monsoon forecasts	Brown and Rogers (2006), Brown et al. (2006)
Water pricing policy design, implementation, and evaluation	Rio Grande Basin, New Mexico, USA	Hydrologic and economic impacts of water pricing programs, equity, water quality constraints	Ward and Pulido-Velázquez (2008, 2009)
Unknown effects of changes in irrigation costs or water access on farmer behavior, incomes	San Francisco Basin, Brazil	Spatially explicit, farm level, PMP model; high-resolution hydrologic model simulates variably saturated subsurface flow and solute transport	Maneta et al. (2007,submitted for publication)
Conflict resolution, transboundary management and sustainability			
Water allocations; growing demands	Israel, Jordan, and Palestine	Cooperation among parties; pricing and social policies	Fisher et al. (2002,2005)
Conflicts between agriculture and Environmental conservation	Syr Darya basin, Central Asia	Long-term modeling with quantified sustainability criteria	Cai et al. (2002,2003b)
Transboundary basin, competition among sectors (e.g. in-stream vs. off-stream) and countries	Mekong River Basin (six countries in SE Asia)	Characterize trade-offs between in-stream and off-stream water uses; hydropower, irrigation, fisheries, wetland water values considered	Ringler et al. (2004), Ringler and Cai (2006)
Bi-national river management	Colorado River; US–Mexico	Cost-effective environmental flows	Medellín-Azuara et al. (2007)
Water scarcity, lack of capital for infrastructure development	Gediz River Basin, Turkey	Multi-objective optimization with heuristic methods and dynamic simulation, included in a stakeholder-driven DSS	Fedra et al. (2007), Cetinkaya et al. (2008)
Managing for climate change and drought			
Droughts in large shared basins	Colorado River, USA	Drought losses to in-stream uses (hydropower, recreation) vs. consumptive uses	Booker (1995)
Effects of climate-change scenarios in large developed economies	California inter-tied system, USA	Infrastructure and policy adaptations for climate warming	Harou et al. (in press), Tanaka et al. (2006), Medellín-Azuara et al. (2008)
Over-appropriation drought and climate change; growing demands	Rio Grande Basin, USA	Institutional adjustments to limit drought damages	Booker et al. (2005), Ward et al. (2006)
Land-use management: floods and water quality			
Quantifying economic impact of European Water Framework Directive (WFD) on agricultural and recreational sectors	Humber Basin, England	Integrate spatially distributed economic, agricultural land use, hydrology and water quality modeling; consider agricultural costs and recreational value generated by WFD	Bateman et al. (2006)
Levee-protected floodplains; adaptation to increasing flood risk	American River, California, USA	Risk-based dynamic programming; flood frequency, levee failure probabilities; hydraulic simulation; maximizes difference between land use value and expected damage	Zhu et al. (2007)
Direct and indirect economic costs of floods	Flood prone areas of the Netherlands	Flood damages and economy-wide effects of floods using spatial hydro-dynamic model	Jonkman et al. (2008)
European Water Framework Directive (WFD) in intensively cropped river basins	Upper Ems Basin, Germany	Spatial DSS links hydrologic, water quality, and economic farm models to estimate economic effects of alternative agricultural management options	Volk et al. (2008)

conflicts. They provide a blue print for collaboration and adaptability that can help move transboundary conflict towards collaboration (Fisher et al., 2005).

Drought and climate change place special stresses on water systems. Hydroeconomic models may provide insights into flexible operations schemes that decrease negative affects of increased water scarcity or other changes.

Land use management for floods and non-point source pollution from agriculture are fertile ground for a new generation of hydroeconomic models. These applications typically link geographical information systems (GIS) to other modeling tools.

Discussion

Policy and institutional implications

Hydroeconomic models have policy implications and uses in several areas:

- infrastructure expansion and operations planning,
- water allocation and markets,
- adaptation pathways (e.g. to climate change)
- design of institutional policies to achieve environmental, social and economic targets (governance, rights, etc.),
- economic policy impact analysis, and
- basis for regulation and law.

Most applications of hydroeconomic models, as reviewed above, are for infrastructure planning and operations, water allocation and markets, impact analysis and adaptation.

Several institutional and policy approaches have been proposed to encourage economic efficiency in water management. Idealized water markets achieve the conditions of economic efficiency by encouraging resources to move from lower to higher-valued uses. Various water marketing strategies have been applied (Lund and Israel, 1995; Easter et al., 1998). The introduction of water markets and water banks has made it possible to balance supply and demand and to lessen the effects of severe droughts (Howitt, 1994; Booker et al., 2005). Water markets are also prone to market failures, especially because of the presence of externalities, natural monopolies, and public goods competing with private demands (Young, 1996). Market failures can be corrected, or at least reduced, by introducing appropriate water right and incentives structures (Burness and Quirck, 1979; Griffin and Hsu, 1993; Spulber and Sabbaghi, 1994).

In cases where the supply has to be controlled by government, efficient price is an administrative tool for water demand management. When the price of water reflects its true marginal cost, including environmental externalities and other opportunity costs, the resource will be put to its most valuable uses (Rogers et al., 2002). Several international institutions have promoted the principle of full cost recovery (OECD, 1999; EC, 2000) and many countries are now engaged in some form of pricing reform (e.g. OECD, 1999; Dinar, 2000).

In any case, efficient water use fundamentally recognizes water's opportunity cost (Griffin, 2001, 2006). Despite the concept's apparent simplicity, measuring the opportunity cost of water is difficult. In the absence of well-functioning water markets, opportunity cost assessment requires a systems approach and assumptions about real impacts and responses (Briscoe, 1996). This assessment has to be based on an accurately specified system to identify and estimate the value of water for the different users in the system, such as hydroeconomic models.

Hydroeconomic models help investigate changing institutional processes to improve water management. Representing the physics, constraints and objectives of water systems helps water management agencies assess and formulate policies and communicate more clearly with stakeholders.

Limitations and challenges

Some authors have taken a critical look at whether systems analysis is useful to improve water management (e.g. Rogers and Fiering, 1986; Bredehoeft et al., 1995). These authors argue that benefits revealed by optimization solutions are often small due to the relative flatness of objective functions near the optimum and the wide range of nearly optimal solutions. Application of optimization models and their recommendations has remained a challenge (Rogers and Fiering, 1986).

Including economic criteria adds a layer of theory and complexity beyond traditional water planning models that may be difficult or controversial for water managers to accept. To achieve relevance outside of academic and policy circles, hydroeconomic modelers must work with or among real water managers, use and extend established models, develop and incorporate economic data, and offer user-friendly software.

Several difficulties exist to directly use hydroeconomic model results. Simplification and aggregation of physical, economic and regulatory processes and data is necessary for timely construction and resolution of regional models. If physical aggregation is coarser than existing simulation models, managers may perceive the hydroeconomic model as too theoretical or insufficiently detailed to support local decision making. Models with simplified process equations also place increased pressure on the reduced parameter set to accurately represent the system. Simplification may contribute to lack of robustness at the local scale; for example a small change in cost on a link in a network model could cause flows to take a dramatically different route. However, at the larger regional scale such local effects tend to balance out leading to generally robust system-wide results in terms of major trends and responses to different scenarios and policies. It is also difficult to make simplified regional models agree with observed data and calibrate these models to historical data (Draper et al., 2003; Cai and Wang, 2006).

Linearization of non-linear functions or physical process equations is often employed to allow the use of linear programming, which guarantees a global optimum. If non-linear equations are used, model size is often further reduced for computational reasons.

Shadow values, range-of-basis, and sensitivity analysis provide important information on marginal values and changes in system performance related to numerical and other uncertainties. However, they must be evaluated reactively "one-at-a-time" and ignore complex interplays and simultaneous changes among constraint limits, system configurations, and/or prices. Hydroeconomic modeling could benefit by applying proactive approaches to handle simultaneous uncertainties well known in operations research such as robust, probabilistic (chance constraint), and flexible programming (Sahinidis, 2004).

Another difficulty is moving past the idea that hydroeconomic models necessarily impose market solutions to water resources problems. In fact, hydroeconomic models can be poor tools to simulate actual water markets since individual agent behavior and transaction costs cannot be represented easily (Young, 1986; Griffin, 2006, p. 356). For historical and institutional reasons, most real water resources management schemes are not perfect; they inevitably result in some inefficiency. Hydroeconomic models can help identify areas where past water management practices are no longer in synch with current resource availability and current social attitudes towards environmental quality and equity. Using hydroeconomic models helps improve transparency and rationality in natural resource use rather than advocating a particular

ideology. Hydroeconomic models help guide (Fisher et al., 2002) policy makers to formulate effective policies; they are not a policy in themselves.

A further difficulty is mathematically representing social, political and environmental objectives in addition to modeling complex processes. Economic objectives have the advantage of summarizing all interests in a single financial metric, reducing a multi-objective problem to a single objective. However, this reduction in solution effort requires additional data collection: estimating economic values of water uses in the study area. Difficult to quantify objectives often include environmental, ecological or social equity. It may be easier to consider some objectives in non-economic terms, e.g. minimizing differences between releases and the natural flow regime (Tisdell, 2001) to encourage a natural flow regime. Most interests that are not evaluated economically, because of controversy or lack of data, can be represented with constraints to reflect social, political or environmental priorities.

However, certain social priorities such as decision maker risk aversion are not readily represented in either hydroeconomic model objectives or constraints. Hydroeconomic model objective functions typically seek to maximize expected net benefits (or minimize expected costs) where benefits and costs are strictly weighted by their occurrence probability. However, this risk neutral expression undervalues the desire of most decision makers to avoid severe consequences of extreme (albeit unlikely) events. Unrealistic levels of risk neutrality can be partially removed by including penalties for failing to achieve allocation targets. When such constraints are small but have a significant effect on allocations they are referred to as persuasion penalties. Alternatively, supplemental terms can be introduced into the objective function, such as terms that minimize the variance between minimal allocations and economic ones. These approaches are stopgap measures and more advanced methods to represent risk aversion exist in the economics literature (Markowitz, 1959; Sandmo, 1971; Levy and Levy, 2004).

The above factors contribute to the limited application of hydroeconomic models for actual water resource planning and management outside of strict academic and policy settings. An exception is narrowly focused single-objective hydropower applications.

Cost-benefit analysis remains the most widely used economic technique in the water field. This method helps assess the merit of a particular water infrastructure investment while hydroeconomic models focus on operation and design of systems. Unlike traditional benefit-cost analysis, hydroeconomic models provide a way to measure and consider the opportunity costs in water allocation. While benefit-cost analysis provides a single aggregated indicator of economic desirability of a project (i.e. net present value; benefit-cost ration; rate of internal return), the hydroeconomic models show the dynamic variation of water values in time and space. As management shifts from building new water supply systems to better operating existing ones and adopting demand management and water marketing strategies with increasing water scarcity and water conflicts, this more flexible and detailed form of benefit-cost analysis will become increasingly useful (Ward, 2009).

As with all environmental modeling, uncertainty and error propagation are especially challenging; most hydroeconomic modeling efforts barely mention them. A pragmatic approach reiterated by Jakeman and Letcher (2003) and Cai (2008) is to use sensitivity analysis to reveal parameters or model components with the greatest effect on results.

Current trends and future directions

Many current and future water management problems are characterized by a pervasive rise in water scarcity, lack of easily developed new supplies, and increased levels of drought and extreme events from climate change. In addition, there is a growing priority for environmental flows that require that water be managed in an integrated and sustainable way. These trends mean that by choice or necessity, the more effective management of existing supplies will increasingly be chosen over developing new ones. This focus will increase the relevance and need for integrated water management techniques such as hydroeconomic modeling.

Although constraints are typically used in lieu of direct economic valuation of environmental benefits, advances in environmental benefits estimation should allow future hydroeconomic models to include more of these benefits in economic objective functions. For decades recreation benefits were considered "intangible", but are now often included.

As optimization solvers improve, optimization models can incorporate more spatial detail and more detailed physical modeling (e.g. spatially distributed groundwater flow, stream-aquifer interaction, routed surface flows). Incorporating water quality processes will be especially important (Lefkoff and Gorelick, 1990b; Bateman et al., 2006).

Most hydroeconomic models are custom-built, often using commercial optimization software. With economic criteria gaining acceptance for representing system performance, hydroeconomic models will continue to appear in decision support systems (DSS) ("Software implementation") or integrated assessments (Letcher et al., 2006). This trend will accentuate as optimization capabilities are more frequently available in water resource DSS. Generic model platforms (Harou et al., 2009), that connect existing models to a geographical user-interface and data manager will also facilitate development and use of hydroeconomic models. Calibration methods (e.g. Howitt, 1998; Cai and Wang, 2006) for optimization may also be integrated into future practical applications.

The ability to analyze economic impacts of different system designs or management policies is significant. Although there is an inevitable gap between modeling research and its application in decision making, this gap should decrease as hydroeconomic models are included into collaborative planning processes such as shared-vision planning (Palmer et al., 1999; Stephenson et al., 2007) or integrated assessments (Parker et al., 2002). Synthesis of what inherently is a multi-objective problem into a single economic objective is both a strength and weakness of the approach. Solutions proposed by hydroeconomic models will have the most credibility if they are advanced with broader perspectives that consider the problem from many angles. Hydroeconomic models should be useful in shared-vision planning and integrated assessments by providing useful information to negotiators. Making the economic impacts of any proposed water policy or management scheme explicit will increase transparency and empower those who take part in the decision processes.

Conclusions

Hydroeconomic models represent hydrologic engineered systems while explicitly considering the economic nature of water demands and costs. Beyond minimizing costs or maximizing profits, they provide a framework to consider the value of water services in planning and operation. A variety of techniques exist to estimate the economic value of water uses. Managing for water value allows the water system to be dynamic and quickly respond to economic, social, and environmental changes.

Numerous efforts dating back at least 40 years have integrated economic and engineering realities in mathematical models to recommend improvements in the design, operation, and reoperation of water systems. Applications have spanned the globe and addressed numerous problems including: on- and off-stream intersectoral

allocations, water supply, infrastructure capacity expansions, conjunctive use of surface and groundwater, institutions, markets, pricing, conflict resolution, transboundary management, climate change, drought response, flood response, and water quality.

Many choices confront the hydroeconomic model builder; foremost is what questions is the model being built to address? Subsequently, the modeler must choose whether to simulate or optimize, include environmental values and benefits in the objective function, adopt a modular or holistic design, and how to represent time in the model formulation.

Until now, hydroeconomic modeling has been practiced in academic and policy circles with limited implementation of study recommendations by water managers, operators, and practitioners. Hydroeconomic modelers can improve the impact of their work by collaborating with practitioners and extending existing (and trusted) operations models to include hydroeconomic components.

In the future, we foresee increased use of hydroeconomic models to study water transfers, re-operations, and water-use efficiency rather than new supply or infrastructure developments. Also, to include environmental and recreational values in the economic objective function, more spatial disaggregation, and more attention to water quality and uncertainties. Finally, particularly promising is use of hydroeconomic models within collaborative conflict resolution approaches such as shared-vision planning.

Combining engineering, economics and hydrologic science, a hydroeconomic approach is well positioned to help foster integrated water resources management. Hydroeconomic models can help guide policy making and reveal where innovative and dynamic policies can replace outdated arrangements. As water scarcity caused by increased demand and lack of new supplies increases worldwide, resource managers will increasingly turn to tools which reveal with transparency where greater efficiency in water use can be attained. Hydroeconomic modeling can help water managers more effectively steward water resources and provide the best possible water supply and environmental quality to their constituents.

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