

Economics and the Modeling of Water Resources and Policies

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Abstract

Over the last twenty-five years economic water policy models have evolved in concept, theoretical and technical methods, scope and application to address a host of water demand, supply, and management policy questions. There have been a number of theoretical and empirical advances over this period, particularly related to estimation of nonmarket, public good water-related values involving different methods of valuation. We discuss modeling advances including modeling multiple, competing demands, types of incentives and technologies and behavioral responses, incorporation of groundwater and other supply alternatives, integration of institutional factors and increasing attention to system wide impacts. The largest changes in hydro-economic policy models have been the integration of the individual demand and supply components, inclusion of environmental values, incorporation of governance and institutional conditions (laws, regulations and policies), and expansion to river basin and even inter-basin scales of analysis. Important areas of future hydroeconomic model advances will be the use of genetic and neurological based algorithms for solving dynamic, stochastic problems, reconstruction of hydrological and economic relationships for remotely sensed data, and the expansion of models to understand and address transboundary water resource economic, hydrologic, environmental and institutional policy and interdependencies.

Key Words: economic modeling, policy analysis, water resources, hydroeconomic models, integrated models, water value, water demand, water supply, benefit-cost

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Economics and the Modeling of Water Resources and Policies

1. Introduction

Water is a unique substance in the types of goods and services provided to mankind. Using the classification system proposed by Ostrom (2010) and her colleagues, goods may differ according to, first, the degree to which use is subtractable (one person's use reduces potential use by others) and second, to the extent of exclusion and transactions costs (the resources required to exclude potential beneficiaries for nonpayment and enforce exchange contracts). Goods or services which are highly subtractable but exhibit a low rate of exclusion costs are usually exchanged on markets and are called *private goods*. Conversely, those goods which exhibit low subtractability and high exclusion costs are termed *public goods*, and are usually provided by some non-market mechanism. Examples of water as pure private goods (highly subtractable and readily excludable) are difficult to identify, but treated water available for delivery to retail industrial or household users comes closest. Water in surface watercourses, in underground aquifers and even diverted from its natural state exhibit both high subtractability and high exclusion costs, and so are termed *common-pool* resources. Water-related *public goods* (low subtractability; high exclusion costs) are exemplified by water quality improvement projects, by flood-risk reduction programs, or by provision of natural recreational and aesthetic services of rivers, lakes and reservoirs. On other normative dimensions, the necessity of water for life may override economic efficiency considerations, leading to government intervention into supply and pricing of domestic water. Thus, competitive markets seldom are the chosen allocative mechanism for water, and modeling of economic costs and benefits are valuable tools for public evaluation of water policy proposals.

Economists have long been fascinated by issues relating to understanding and managing water resources. An early example is the "diamond-water paradox" that occupied classical economists over two centuries ago. A century later, the very first article in the very first issue of the *American Economic Review* (Coman 2011; original 1911) analyzed issues of organizing and financing of irrigation systems in the arid western US. It wasn't until about a half-century ago that the economics profession began to seriously direct attention to questions of water resource management and policy.

Economic modeling of water resources over the past fifty years has been applied to address a growing number and variety of policy questions. In the late 1950's several economists (e.g. Eckstein 1958) applied the growing theoretical welfare economics literature to issues of water resource investment policy. Spurred by growing computational capacity, the Harvard Water Program developed the first major effort at combining economic concepts with hydrologic models (Maass, et al. 1962). However, the major focus of efforts in the next twenty-five years or so included evaluating the net economic benefits of water resources supply and other physical infrastructure investments, valuation of water in specific uses, analysis of user responsiveness to price, and optimization of water allocation and management issues. Modeling typically represented small spatial areas, and/or addressed specific uses. Examples included farm level crop production models to select a water use pattern to maximize profit, and water reservoir operation models to maximize returns to hydroelectric generation while minimizing evaporative

losses and flood risk. During this earlier period, there was more of a local perspective in the economic modeling of water resources and policy tools.

Increasing water demand, changes in hydrologic, economic and institutional conditions, and also increases in information availability and computing technology, are changing water policy modeling world wide. The growing demand for water across all sectors of the economy, limited availability and high costs of developing additional supplies, combined with the relatively recent recognition and consideration of environmental water demands and value, has lead to competition for existing water resources. Randall (1981) characterized this situation as moving from an *expansionary* water economy where the benefits of developing new supplies exceeded the cost to a *mature* water economy where new supply costs exceed the benefits. Under these latter conditions it is more efficient to reallocate water based on the relative value of each use rather than expand water supplies, if that is even feasible. The role of economics in water policy has morphed from typically benefit cost analysis of proposed single-use infrastructure supply development projects, to analysis of optimal allocation of water across multiple uses (instream and offshore) and water sources (ground as well as surface) over larger hydrologic regions.

Over the last twenty-five years, the focus of this paper, economic water policy models have evolved in concept, theoretical and technical methods, scope and application to address a host of water demand, supply, and management policy questions. To begin, water demand modeling has taken on new importance with the need to better understand market and nonmarket water use values for evaluation of reallocation and investment benefits and policies. There have been a number of theoretical and empirical advances over this period, particularly related to estimation of nonmarket, public good water-related values. Because of the many different types of demand for water, different methods of valuation are needed. Revealed preference and stated preference techniques are being used with a variety of modeling techniques (discussed in the next section) to develop outdoor recreation, water quality, aesthetic, environmental and other water-related market and nonmarket benefit values. An area that can affect both water demand and supply is conservation. Conservation can reduce demand for a particular use enabling the saved water to be allocated to other uses. In order to accomplish this water conservation measures need to be less expensive than the cost of the water saved. We discuss modeling advances in this area including types of incentives and technologies, behavioral responses and increasing attention to system wide impacts (net effects) of conservation policies.

Supply is another side of the water resource policy modeling equation and there have been advances and expanded efforts in several areas. We discuss research on modeling methods to address water supply and allocation in mature water economies, supply alternatives in both mature and expansionary water economies in other parts of the world, the problem of optimizing reservoir water management over time in integrated hydro-economic modeling environments to explicitly address multiple objective tradeoffs and modeling to address questions about the adequacy of water supply sources under changes in climate. Groundwater supply research has moved to the use of dynamic optimization methods with surprising results, analysis of simple “single cell” aquifer models widely used in hydro-economic models, and advances in modeling conjunctive surface and ground water management and policies.

The largest changes in hydro-economic policy models have been the integration of the individual demand and supply components, inclusion of environmental values, incorporation of governance and institutional conditions (laws, regulations and policies), and expansion to river basin and even inter-basin scales of analysis.

2. Modeling Demands for Water and Benefits of Water-Related Investments and Policies

In order to represent the human behavioral portion of integrated water policy evaluation models, and also because of a general interest in describing and explaining economic behavior of water users, economists have expended considerable effort to develop and improve models of the economic demands for water. These demands are many. Most essentially, water is required for human survival, both directly in food and drink, and indirectly in the production of that food. Similarly, water supports the basic ecosystem services to which we are accustomed: a diverse, oxygen producing environment, and reliable biologic waste disposal. Finally, water is used to some degree in the production of virtually all economic goods and services, and has economic benefits in its cultural and religious significance.

A variety of methods for estimating the economic demands for water have been developed to address the specific characteristics and allocative approaches for the diversity of water uses. Following Young (2005), we use the term *inductive* to describe economic modeling techniques implemented via statistical inference from empirical observations, and *deductive* for models implemented by deducing demands and benefits from hypothesized theoretical models empiricized with appropriate case-specific data.

The basic concepts used as measures of demand and value are willingness to pay (WTP) or willingness to accept compensation (WTA). (Freeman 2003 has been regarded as a primary authority on nonmarket valuation theory.). Resources have economic value or yield benefits whenever users would willingly pay a price for them rather than do without, or be compensated to do without the good or service. In principle, operation of a competitive market results in a set of values (prices) that serve to allocate resources and commodities in a manner consistent with the preferences and objectives of consumers and producers. For a number of reasons discussed above, primarily the high cost of excluding potential non-paying beneficiaries, avoiding free-ridership and devising property institutions for accommodating the stochastic natures of water supply and demand--establishing and enforcing property rights--relative to the value of water at the margin--competitive markets for water are rare if not absent throughout the world.

Private goods can be usefully further classified into *producers'* goods and *consumers'* goods. A product or service used to make other goods or services is called a producers' (or sometimes an intermediate) good, in contrast with consumers' goods, which are used directly by consumers. For example, irrigation water is used to produce crops, which, after adding inputs for processing, transportation, packaging, and marketing, eventually become consumers' goods (i.e. food on the table). Water used in households—for drinking, cooking and sanitation—is, in contrast, best treated as a form of final consumers' good. These concepts are important because they affect modeling approaches.

2.1 Modeling Producers' Demands for Water

Producers' uses of water including agricultural crop irrigation and various industrial uses are among the most important off-stream water uses in the world. Crop irrigation is the most significant consumptive user of water on the planet, and very important in countries with arid and semi-arid climates. Industrial water uses include instream electrical energy generation and water-based transportation (primarily non-consumptive) and offstream cooling water for stream-electric power generation.

Agricultural crop irrigation

Beginning with the crop irrigation case, the most common approaches to modeling are the various forms of *residual* valuation. These methods are deductive in that they involve creating models of optimal farm firm behavior and calculating residual scarcity rents to the water resource (estimated returns over non-water costs). Initial models were simple individual crop budgets, later expanded to represent a whole farm. Agricultural economists then began adapting linear programming optimization models (CV Moore and Hedges 1963), in which estimated maximum net farm returns were solved for various hypothesized water prices or various water constraints to trace out step demand functions (inverse demand functions). Various specification issues were debated, including how to measure economic welfare changes, whether certain problem conditions called for (Marshallian) long run or short run models, or whether private or social prices for inputs (e.g. labor, capital) or outputs were appropriate. Early versions allowed only water uses associated with successive reductions in land devoted to lowest-valued crops in response to price increases. More recent models may reflect producer choices among several levels of water use and for alternative water application technologies (e.g. furrow, sprinkler, drip, etc) for each crop. A number of analysts (e.g. Booker 1995) have used regression to smooth the step inverse demand function for subsequent incorporation into a regional water policy evaluation.

A particular issue with residual techniques is the problem of assigning costs to noncontractual or owned inputs (such as risk capital, land and non-field labor). Returns to these inputs, along with rents to water, are determined by the results of management decisions rather than being known *ex ante*. (See Young 2005 for a discussion of these issues and Scheierling, et al. 2006 for a survey and meta-analysis of irrigation water demand studies in the US.)

To circumvent this problem, Howitt (1995) has proposed and implemented a technique called positive mathematical programming (PMP). PMP is a self-calibrating three-step procedure. First, a linear program for profit maximization is solved. Calibration constraints restrict land use and crop mix to observed values. Next, the parameters of a quadratic cost function are derived using Lagrange multipliers from calibration constraints from the first step, and the production function from first order conditions. The third step incorporates the previously calibrated functions into a non-linear profit maximization program, with constraints on resource use. Finally, economic demand functions of water are obtained by solving repeatedly for alternative restrictions on water availability for the study region. See Medellin-Azuara (2009) for a clearly-described instance of this approach.

A number of inductive modeling approaches to irrigation water valuation have also been reported, mainly taking the form of econometric analyses of regional public (e.g. census) data to isolate the contribution of irrigation water supplies to regional economic growth. Lynne (1978) provides a review and critique of the early econometric analyses of irrigation water productivity. Moore et al. (1994), Schoengold et al. (2006), and Nieswiadomy (1985) are important examples of the use of statistical models to measure economic response. These three studies use an inductive approach based on an unusually rich set of data, permitting the authors to estimate the derived demand functions for agricultural water use by conventional econometric approaches. The elasticities of demand resulting from these estimates are particularly interesting. Elsewhere, this inductive approach is exemplified by several national studies (India, China, Thailand) published by the International Food Policy Institute (see, e.g. Fan, et al. 2002) in which returns to investments in irrigation (and to alternative productivity-enhancing expenditures—research, extension, education, transportation) are jointly estimated .

Industrial Water Demands and Valuation

Most of the economic research on industrial water demand has focused on offstream uses in manufacturing facilities: cooling (especially for steam-powered electrical generation), process water, and the small amounts incorporated into products. Additional important industrial water demands are for instream uses, such as hydroelectric power generation and inland waterborne transportation. Among manufacturing facilities, the level of withdrawal ranges from very small (perhaps only for little more than employee sanitation) to relatively large (cooling thermal electric power plants or producing chemical products). The evidence mostly suggests that the contribution of water to the value of industrial production is minor next to other inputs such as raw materials, manufactured parts, capital equipment, labor, and management (Young, 2005, chapter 6).

Residual methods, which in general are flexible and adapted to forecasting the effects of proposed policy initiatives, are deemed less useful in industrial water valuation, primarily because plausible variations in the opportunity costs of owned inputs would probably overwhelm the minor contribution of water to the total value of output.

A useful early survey of issues in industrial water demand analysis is presented in a collection of papers edited by Kindler and Russell (1984; see chapters by Stone and Whittington; and by Russell). Most of the limited literature on manufacturing demand for water have used econometric techniques (inductive) with annual (mostly secondary) data on production and input use from surveys of manufacturing enterprises to estimate the effects of water cost on withdrawals (Renzetti 1992; 2002a). These studies have found the demand for water withdrawn for industrial purposes to be generally price-inelastic. The varied sources of water (both purchased and self-supplied) complicate specifying a variable to represent marginal price or cost of water. Except perhaps in the instream cases—hydropower and waterborne transportation—plausible variations in the opportunity costs of owned inputs would overwhelm the minor contribution of water to the total value of output. In particular, the use of unadjusted value-added measures from regional input-output models should be avoided. Mathematical programming methods based on cost function rather than residual rent models may hold promise, but have

been infrequently attempted. Applied economic valuation of industrial water use still deserves further exploitation by resource and environmental economists.

Another, not often used, deductive method of deriving rents to an industrial project is called the *alternative cost* approach. The method is appropriate when, if a given project of specified output costs less than does the next-best public or private project which can achieve the same output, then the cost of the next best project can be assigned as the gross benefit to the public project under consideration. The savings in costs can be credited as willingness to pay for water. A key condition is that the alternative investment must in itself be economically feasible. The method has been used for assessing hydroelectric power projects, testing to see if and by how much such a power project would save relative to an alternative steam-powered generating plant. See Young (2005, Section 6.6.4) for an example applied to the Colorado River in the southwestern US. The alternative cost method has been applied also to evaluating proposals to invest in inland waterways navigation facilities. For example, Huszar (1998) studied a proposal—called the Paraguay-Parana Project—designed to improve waterway transportation from a port on the Atlantic in Uruguay to Caceres, Brazil. Huszar argued that the proposed investment would be more costly than a rail alternative, particularly when environmental damages to the wetlands of the Pantanal National Park in Brazil were accounted for.

Finally, Barbier's (2004) notable effort that doesn't fit naturally in any other place in this section, adapts techniques and some data of international growth modeling to study whether increasing water scarcity may impose constraints on the growth of countries throughout the world. His cross-country estimations suggest that for most (but not all) economies, at current rates of fresh water utilization, water supplies are not yet constraining growth.

2.2 Measuring Demands for Municipal Water Supplies

Most municipal demand analyses have been econometric studies based on consumption and price data from water supply agencies, whose customers encompass residential, government, and commercial uses. Residential water use includes indoor uses for sanitation, drinking, and cooking, and outdoor uses for lawns, gardens, and occasional washing of cars and driveways. In arid areas, outside uses may account for a major portion of demand, so climatic factors may be important in the demand model. Residential use is appropriately classified as a final consumption good, so the theory of consumer demand provides the basis for studying this type of demand.

Because it was often difficult to obtain data isolating other municipal customers from residential uses, most early investigations of municipal water demand focused on total municipal consumption. The resulting empirical estimates of water demands reflect behavior of a wider range of users than purely household demands. With the increased use of meters to measure deliveries to individual customers and with improved municipal record-keeping, water demand studies can now usually distinguish at least among residential and commercial categories. Most such studies are based on average water use by user class, but some analysts have turned to surveys of individual household water users.

Howe and Linaweaver (1967) first applied modern econometric techniques to residential water demand. They analyzed 1963-65 data from United States suppliers differentiated by region according to indoor and outdoor uses. Water price was represented by the combined value of the marginal water and sewage price blocks in which the average consumption was observed. Quantity was the average water use per account per day. Howe (1982) re-estimated marginal price elasticities with this data, utilizing more appropriate forms of household water demand functions derived from advances in consumer theory that account for the effects of a rate structure. Winter season elasticity was found to be a very low -0.06 compared to -0.23 in the 1967 study. For summer demands, price elasticities are found to be lower than earlier estimates, namely, -0.568 versus -0.860 for eastern U.S. areas and -0.427 versus -0.519 for western areas. Renwick and Green (2000) analyzed cross-section monthly time-series data for eight large water agencies in California for the period 1989–1996 to isolate the effects of non-price conservation policies and water price. They report that both price and demand-side management policies reduce residential use of water.

This topic is the subject of a fairly extensive literature, and several surveys and meta-analyses are available. Hanemann (1998) reviews the theory and application of residential water demand analysis and identifies more than 50 articles and reports from the pre-1992 literature in the United States on the subject. Renzetti (2002b, Chapter 3) provides another wide-ranging summary of the literature, with a commentary on methodological issues. Worthington and Hoffman (2008) survey a sample of post-1980 water demand literature. The data base of the most recent meta-analysis (by Dalhuisen et al. 2003) includes 314 price elasticity and 162 income elasticity estimates from 64 studies. The sample median price elasticity is reported as -0.35 and the median income elasticity is 0.24 .

Several specific analytic issues have occupied students of municipal and domestic water demands. Among these are: type of data (cross-section or time series; total utility supplies and price vs. observations on individual households). Probably the issue that has received the most attention is whether the price variable should be average revenue (roughly revenue divided by water deliveries) or marginal price. One of the earlier studies (Foster and Beattie 1983) argues for average revenue, hypothesizing that because water is a small portion of household budgets, consumers give little attention to the decision, and average price is the appropriate indicator of behavior. Also, average revenue is much easier to measure. In a number of studies, this position has found empirical statistical support in their goodness of fit tests. The alternate view (marginal price as the variable) bases its case on economic theory assuming well-informed consumers. Taylor et al. (2004) show that when the water price schedule includes a fixed fee, as it often does, the improved goodness of fit for the average price formulation is more a statistical artifact from the unitary elastic identity created when the price schedule includes a fixed fee than an empirical confirmation of consumer behavior. Taylor et al. found that once fixed fees were purged from their sample of Colorado domestic suppliers, the marginal price specification yielded a less-elastic demand function and a better statistical fit.

Treated water delivered to customers is a much different product than is raw water at the point of withdrawal or capture. Significant resource inputs are involved in the capture, storage, treatment, and pressurized delivery of raw water to the customer. Many cost-benefit studies, particularly those evaluating potential rural to urban reallocation require that the benefit measures of urban

demand be commensurate with that of agricultural demand. In such cases, it is most convenient to value both sides in terms of raw water. Converting the estimated demand for delivered water into the derived demand for raw water can be done by a method called *point expansion* (Griffin 2005; 277-79). The method, to our knowledge first used in the water economics literature by James and Lee (1971), extrapolates a function from knowledge of a price-quantity point on the function and of the elasticity or slope of the function at that point. Given the expanded demand function, the consumer surplus can be inferred and a derived demand for raw water calculated by subtracting costs of treatment and delivery.

Turning to residential water demand in developing countries that lack meters, little research has used the standard econometric analyses employed in the United States and elsewhere in the developed world. However, Saleth and Dinar (1997), as part of a larger study on municipal water supply policy in Hyderabad, India, performed a sophisticated econometric investigation of domestic water demand for that city. In contrast to the focus on village water supply of most developing country applications, Hoehn and Krieger (2000) investigated residential water supply and sanitation issues in Cairo, Egypt. Using contingent referendum valuation, the authors studied analysis of four aspects of residential water supply: willingness to pay for water connection, improved reliability of existing water service, wastewater connections, and network maintenance to eliminate sewer overflows.

In the many smaller developing country municipalities where water supplies are not metered, researchers have adopted stated preference methods. Whittington and Swarna (1994) summarized early research into economic benefits of potable water supply projects in developing countries. They discuss and illustrate the use of cost saving, contingent valuation, and hedonic property value methods. Whittington, et al., (2009) survey the theory and evidence regarding improving water and sanitation services in less-developed countries, and for four case studies, report Monte-Carlo simulations that assess investment alternatives.

2.3 Modeling Benefits of Supplying Water-Related Public Goods

We now take up methods for valuing water-related environmental public goods, where use of the good in question is non-subtractable and it exhibits high exclusion-cost. Where water yields a public good, and neither diversion for production nor prices for private purchases exist, special data collection and demand evaluation methods must be adopted. These instances are often associated with both use and non-use (or passive) values for outdoor recreation, aesthetic enjoyment of water in its natural surroundings, water quality improvement, and other environmental benefits. Streams and lakes valued for aesthetic or recreational pleasure furnish one instance; one person's enjoyment of a beautiful waterfall doesn't reduce the enjoyment of others (congestion aside). Water quality improvements, flood risk reductions and non-use values (such as biodiversity preservation) are other water-related largely public goods.

A number of methods have been developed for measuring benefits of environmentally-related water uses. *Revealed preference* methods rely on actual expenditure choices for environmentally-related private goods made by consumers. *Stated preference* methods involve asking people in relevant populations directly about the values placed on proposed or hypothetical changes in

environmental services. In the terminology introduced above, both approaches are inductive, in that they use statistical or econometric methods to infer willingness to pay for environmental services from behavioral observations or consumer surveys. Benefit transfer is often used where limited study resources prevent application of the other methods. It uses benefit or value estimates derived from earlier similar studies to provide estimates for new cases. Meta-analysis, the process or technique of synthesizing research results by using various statistical methods to retrieve, select, and combine results from previous separate but related [studies](#), can be also be used as a basis for benefit transfer. (See Champ et al. 2003 for a collection of competent analyses of the various methods for valuing environmental public goods.)

2.3.1 Revealed Preference approaches

Two principal types of revealed preference methods are applicable to environmental valuation. One is the group of recreational demand models, exemplified mainly by the *travel cost* method, which infers the value of a recreational site from data on the varying expenditures incurred by consumers to travel to the site. The other is the hedonic property value model, which measures the difference between real property prices (usually residential housing) exhibiting varying environmental qualities to infer value placed on improved environmental quality. The principal attraction of the revealed preference approaches is that they reflect actual consumer choices. Bockstael and McConnell (2007) set out the theoretical issues in measuring environmental values via revealed preference methods.

Travel cost studies obtain data primarily from interviews of recreationists. Early travel cost approaches (particularly in the grey literature of consulting reports) used total expenditures by recreationists to measure demands. Subsequent approaches aimed at deriving an estimate of consumer surplus (theoretically appropriate but empirically smaller and much more difficult to quantify). A number of practical issues are encountered in assembling the data set. For example, does the vehicle cost include only the immediate out-of-pocket costs, or should full running costs (including depreciation, insurance, etc) be included? Should availability of substitute sites be accounted for? Burt and Brewer (1971) first formulated a multiple site travel cost model to account for substitute reservoir sites. Should the opportunity costs of travelers' time be included as a cost, and if so, how should it be priced? Tests of the sensitivity of consumer surplus estimates to alternative functional forms but using the same data have found large differences depending on the functional form chosen. For example, from a single data set reported in Garrod and Willis's (1999, 65) study of visitors to canals and waterways in the United Kingdom, consumer surplus estimates ranged from 0.50 UK pounds per day (linear model) to infinity (double log model). A particularly rigorous example of the travel cost method applied to water is found in Ward et al.'s (1996) study of drought impacts on travel to a set of California reservoirs.

The hedonic pricing method rests on the assumption that the price of some marketed good is a function of its different characteristics, and an implicit price exists for each of the characteristics. For valuing environmental attributes, hedonic pricing is used most often to analyze data from the residential housing market. This analysis tracks prices of real property (land) that exhibits varying environmental characteristics (e.g. water qualities, water supplies), so it is usually called the hedonic property value method. The model hypothesizes that the utility of consumption of housing services depends on the structural characteristics of the dwelling, a vector of

neighborhood characteristics (accessibility to jobs, shopping, and parks; crime rates) and location-specific environmental amenities. Water quality and water level in lakes or reservoirs adjacent to residential or recreational homes are of interest here. Econometric methods are applied to isolate the incremental effect of the environmental variable on the market value of real estate, with the incremental effect being a measure of the environmental value sought. See Boyle and Kiel (2001) for a survey and assessment of the earlier examples of the literature on the effect of environmental variables (including water quality) on housing prices.

2.3.2 Stated preference methods

To implement a stated preference analysis, respondents are presented a description of conditions simulating a hypothetical market in which they are asked to express WTP for existing or potential environmental conditions not registered on any market. The original and still most common form of questioning to ascertain individual valuations of hypothetical future events is called the contingent valuation method (CVM). Respondents, who may be surveyed by direct or telephone interviews or by mail survey, are asked to provide WTP for moving from a given state of affairs to a supposedly more desirable one.

A number of water-related CVM studies were reported beginning in the 1970s, including Hammack and Brown (1972) on wetland preservation for wildfowl habitat. Loomis et al. 1991 and Loomis et al. 2000 report other examples of the approach. Some observers have been skeptical of the validity of valuations obtained via this method. Improvements in questionnaire design and in statistical methods have dissipated some of this concern. A meta-analysis by Rosenberger and Loomis (2000) found that there were no significant differences in value estimates performed with stated preference or revealed preference methods. Carson and Hanemann (2005) provide an extensive and authoritative review and assessment.

Recently, some researchers recommend *choice modeling* (CM) analysis (or conjoint analysis). This approach presents the respondent with a set of policy options, each described by a cost and a complete set of attributes or consequences of choosing that option (Bennett and Blamey 2001). The respondent is asked either to rank the options or to choose the preferred one. Statistical analysis, usually within the random utility maximization (RUM) modeling methodology, is then applied to infer monetary WTP for various attributes of the policy options.

For cases where both methods are appropriate, analysts are increasingly combining stated preference and revealed preference methods, on the finding that the combined approach yields better results than does either used separately. Whitehead et al. (2010) describe and assess this approach.

3. Conservation, Incentives, and Management Practice

Understanding of the economic demand for different water uses is one basis for the modeling of policy tools to address general water management objectives. This work was well represented 25 years ago, with substantial effort focused on consumer and producer responses to policy initiatives in well defined and localized partial equilibrium models. Dynamic adjustments were

largely limited to short run behavioral changes (e.g. labor-water input substitution) or to a limited menu of technological adjustments (e.g. changes in irrigation technology or cropping patterns).

One perspective on recent advances in modeling to support conservation objectives has been increasing attention to evaluating impacts within a systems framework. This has required in many cases more disaggregated and realistic modeling of system hydrology, and increased formal and explicit attention to third party impacts. The integrated hydroeconomic models increasingly used to address not only conservation, but also more general water allocation questions are discussed in the following section.

In advances following more traditional disciplinary paths, theoretical models now suggest that long run producer responses including firm size may be particularly important in evaluating conservation policy. Related to this idea is growing recognition and emphasis that water use and trade in foodstuffs is the broader context of water management. This perspective leads in one line of work (e.g. Berck, Robinson, and Goldman, et al. 1991) to the development of computable general equilibrium (CGE) models. An alternative emphasis is a focus on the water intensity of traded (primarily agricultural) goods. Following this emphasis, recent work on developing water footprints is a natural outgrowth of water modeling to address conservation objectives.

Gardner and Young (1988) provide a representative example of modeling conservation policy. In this study, local producer responses to alternative on-farm salinity control strategies in the Grand Valley in the Upper Colorado River Basin in the southwestern United States are modeled. Gardner and Young investigate a number of cost-sharing mechanisms giving net economic benefits (considering only salinity) which might be acceptable to both Grand Valley irrigators and lower basin Colorado River users. An important producer response to the menu of policy incentives is to adopt technologies (e.g. sprinklers) which reduce return flows thereby limiting leaching of salts in local soils. Their example of policy approaches to address a system-wide salinity problem shows how modeling work of the time was already directly motivated by basin (system) perspectives in addition to local impacts. But the work also suggests modeling advances which subsequent work illustrates. Dynamic responses to firm size and cropping acreage were limited by methodology and assumptions, while a focus on salinity limited formal consideration of changes in downstream instream water use values (e.g. for hydropower production) and on impacts to downstream offstream water users.

While reducing diversions and water application, field level water saving technologies adopted in response to conservation incentives could in theory fail to reduce consumptive use. Huffaker and Whittlesey (2000) identify exactly this response in their work applied to the Snake River Basin in southern Idaho. The key formal advance is the addition of multiple diversion points, with return flows from and consumptive use by upstream irrigators substantially impacting supplies available for diversion by downstream irrigators. Following this modeling approach, Huffaker and Whittlesey demonstrate that investments in water efficient irrigation technology, while profitable for individual producers under typical water conservation policy, can in aggregate be detrimental. The mechanism is intuitively clear: if policy allows water diversion savings to be spread to additional acreage, the net result is increased consumptive use, to the detriment to downstream and/or more junior irrigators. Incorporating the flexible acreage with a basin-wide perspective allows the model to capture dynamic adjustments to policy resulting in

unintended perverse impacts. More generally, Huffaker and Whittlesey's work clarifies the centrality of consumptive use (as opposed to diversions or withdrawals). Their work also points to developments in integrated hydroeconomic modeling incorporating water and environmental demands of multiple stakeholders, potentially linked through complex physical processes (e.g. Jakeman et al. 2006) and even trade channels. For example, Rosenberg, Howitt, and Lund (2008) address the benefits of conservation in a model which introduces stochastic supply and links multiple water users while allowing for infrastructure expansion and conjunctive ground and surface water use. With the richness of the modeling environment multiple economic and non-economic management practices are found to be effective in reducing the need for infrastructure expansion.

While much of the work modeling conservation utilizes the integrated hydroeconomic modeling discussed in the next section, more parsimonious approaches are also revealing. One conclusion of work on conservation incentives is that water prices should, at the margin, reflect opportunity costs. In both municipal and agricultural water use contexts this has frequently led to the conclusion that prices should match the frequently high opportunity costs at the margin (on efficiency grounds), with considerably lower average prices (on equity grounds). In short, some form of increasing block rate pricing is recommended. In simplest form this is a flat water connection fee which provides a fixed delivery supporting some notion of basic needs, followed by a per unit charge for higher deliveries which is set at the opportunity cost of new water supplies in the region. In practice, multiple blocks are typically used, and the relationship between the water charge for the highest block and opportunity cost may be tenuous at best. A basic criticism of block rate pricing is that water users may respond more to average price than to marginal price. For example, research on residential water demand block rate prices applying econometric techniques developed for electricity demand to determine whether consumers respond to average or marginal price was inconclusive (Michelsen et al. 1998). But Taylor, McKean, and Young (2004) show that a properly specified model can in fact lead to the conclusion that consumers are responsive to marginal price. Regardless, water use is clearly also responsive to nonprice measures such as retrofit and regulatory programs (Michelsen et al. 1999). These types of findings contribute to the frequent inclusion in water modeling of the nonmarket and institutional factors discussed in the next section.

An additional and important direction of work is to consider impacts of the long run incentives of water pricing. Writing in *Natural Resources Modeling*, Bar-Shira and Finkelshtain (2000) address increasing block rate pricing when farm size and number is endogenous. In the context of a competitive industry with free entry and exit, they demonstrate that in comparison to flat rates, increasing block rate pricing may be desirable on equity grounds (preserving the number of farms), but is inefficient because it results in overproduction and too many small firms relative to the welfare maximum. But in a subsequent application, the inefficiency is estimated at only 1% of the value of agricultural output (Bar-Shira, Finkelshtain, and Simhon, 2006). This strand of work illustrates a continuing need to move beyond responses of existing water users in modeling work, to consider the dynamic incentives of water policy. It also demonstrates the importance of placing empirical estimates of unintended policy consequences in context.

4. Models Integrating Water Supply and Demand

While our increasing understanding of the economic demand for water is a useful starting point for addressing conservation impacts of incentives, this work by itself cannot address critical policy questions of water resource allocation and development. For this, models which incorporate both the physical hydrology and supply costs are needed. While the latter is typically straightforward, modeling relevant hydrologic characteristics poses a major challenge in the economic modeling of water. And for many water allocation questions, understanding and representing the institutional environment is also needed. In the typical deductive models, two key features characterize economic models of water allocation.

First, economic equilibria in water allocation are almost always constrained in terms of the physical ability to supply, store, and transport water. By their nature, water demands and supplies are typically seasonal, stochastic and spatially differentiated. It follows that to be of practical policy use, models need an explicit empirical hydrologic structure that must accompany and constrain the economic allocation of any water resource. The second feature that determines the structure of hydroeconomic models is that most water demand and supply prices are not normally the result of unfettered supply and demand interaction. The supply of water is normally proscribed not only by hydrology, but also by complex historical institutions that modify price signals, and often substitute for market prices. Urban water systems often yield good price data, but prices observed for rural water demands and urban and rural supplies are rarely the result of conventional economic optimization. Since observed prices cannot be assumed to be the result of market optimization, the majority of hydroeconomic models impose an explicit optimization process on the fundamental economic costs and demands subject to institutional constraints. A survey article by Harou et al. (2009) reviews hydroeconomic models from the hydrologic perspective.

These requirements result in a class of models in which the economic, institutional, and hydrologic systems are explicitly defined in a specification that captures the dominant spatial and inter-temporal interactions between the two systems. The wide range of model specifications and different policy questions require different modeling approaches, but these two characteristics are common to all hydroeconomic models. In this section we consider first the basic methods and approaches used by integrated models. We then consider advances in policy modeling to address use of surface water, groundwater, and integrated surface and groundwater supply systems, and the impact of climate and emerging supply sources such as desalination. Our discussion of hydroeconomic models represents an idiosyncratic view with many omissions and possibly accidental misrepresentations by the authors.

4.1 Why We Need Integrated Models

Over the previous era there has been a basic change in the demand for and nature of economic models of water allocation. At one time increased water supplies were met by building infrastructure that would capture more of the existing surface water flows. For such projects, the role of economics in the water sector was essentially that of an ex-post justification of the optimal engineering specification of the infrastructure. This past era of water development,

termed the expansionary phase by Randall (1981), as well as the hydraulic era by Hanak et al. (2011), was ending in the western U.S. between 1960 and 1980, and is now clearly over. The role of economics in the water sector has morphed from this ex-post evaluation, usually by benefit cost measures, to an ex-ante measure of the optimal allocation of water, including demand modification and supply reallocation and development. More importantly, economic mechanisms have been recognized as driving much of the reallocation of existing supplies by water markets and other potential incentive based mechanisms (e.g. water quality objectives can be achieved at a lower cost using such institutions as “cap and trade”). Another cause of the growth and change in hydroeconomic models is the definition of water resource objectives to include explicit measurement and sometimes evaluation of environmental outcomes dependent on water.

The changed demands for water modeling have called for different types of models. In this review we categorize models not by their economic properties, but by the policy question they have to address, or their methodological focus. Since water policy has both, physical, environmental and economic goals, a policy model without explicit spatial or inter-temporal linkages is misspecified. Likewise, a hydrologic model without an economic objective function is also misspecified as it ignores a critical motivation for water policy. Most uses of water have explicit economic values, and for those uses based on physical environmental criteria, the presence of economic values in the alternative uses results in most environmental policies having implicit economic values, if not explicit ones.

4.2 Integrated Modeling Methods

Typical hydroeconomic models are developed as constrained optimization problems. Economic measures of the benefits and costs of water use are used in the objective function, while hydrologic and other factors are generally represented as constraints. Additional constraints are used to represent the institutional environment, and frequently environmental constraints (e.g. minimum instream flow requirements). Such models can be used for surface water dominated policy issues, ground water issues, or physical environments in which combined ground and surface water use are important. Multiple supply and demand nodes are often present, allowing for substantial spatial disaggregation. Holistic modeling approaches of this type are the focus of this section which integrate economic, hydrologic, institutional rules and policy instruments to identify and understand interrelationships and analyze potential methods to achieve desired objectives [conceptually illustrated in Figure 1]. An alternative modular approach to hydroeconomic modeling is to sequentially or iteratively apply distinct economic and hydrologic models to address policy issues. This type of modeling approach is not the focus of this paper. See Table 1 in Harou et al. (2009) for a brief summary of the basic alternative approaches to integrated hydroeconomic models.

A number of alternative approaches have been used for representing outcomes over time. Single models can be solved sequentially to give estimates of water use over time, or single solutions using explicit assumptions on future expectations can be obtained. These alternative approaches lead to the classification of integrated static or dynamic models discussed in sections 4.2.2 and 4.2.3.

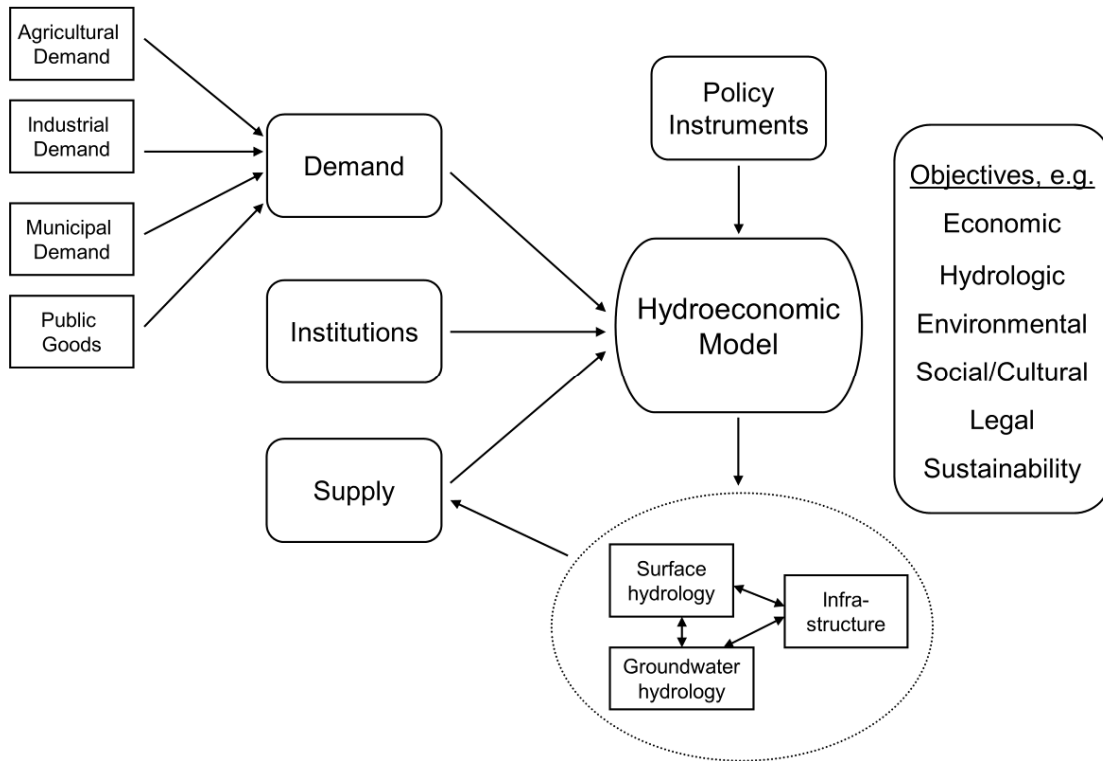


Figure 1. Basic conceptual structure of integrated hydroeconomic models.

4.2.1 Representing Economic Decisions by Water Users

The standard approach for hydroeconomic models is to use some measure of economic well-being in the objective function. This measure is usually a combination of producer surplus and consumer surplus, and occasionally a simple measure of farm profits is used to represent optimizing farm behavior. Examples of more recent models that are driven by maximizing measures of producer and consumer surplus include the Swap model in Howitt et al. (2001)-- which uses a non-linear calibration approach -- and the model developed by McCarl et al. (1999) which uses a linear programming approach, or the review paper by McKinney et al. (1999) that assesses several basin-level approaches. There is also a large class of simulation models which are predominantly hydrologic and subject to constraints and allocate water by priority rules. Examples of such models are the WEAP (Yates et al. 2009) and the CalSim II model (Draper and Lund 2004). This latter type of model is not reviewed here since they are strictly hydrologic models and do not include a measure of economic well-being in their objective functions.

4.2.2 Representing Hydrology

Hydroeconomic models typically represent hydrology through a series of constraints. Most simply, a one period model allocating use between competing water demands would constrain total use to the available resource. In practice, mass balance constraints of this type are used to represent conservation of surface and ground water stocks and flows across time and space. Complex processes such as infiltration and ground-surface water interactions are typically represented by constraints which parameterize results from specialized hydrologic modeling. The level of complexity utilized varies widely, and is dependent on policy questions, the physical environment, and the intended audience. In typical spatially explicit models it is not uncommon to have thousands of equations representing the hydrologic constraints.

4.2.3 Incorporating Institutional Rules and Constraints

Water allocation institutions have emerged over a long and contentious history as a complex set of local rules, regulations, and rights. These can be modeled by sets of constraints and allocation priorities in the spatially explicit models that we discussed. One of the major policy advances in water resource allocation in recent years is the gradual replacement of fixed allocation rules by market-based institutions. The testing of the economic impact of such institutional changes has been a natural extension for hydroeconomic models with their detailed specifications and physical constraints on the ability to move water between different locations. The simplest and easiest way to specify hydroeconomic models is in the perfect market equilibrium situation without additional property rights constraints. The ability to represent alternative levels of market innovation in water resource allocation comes naturally to such models. Examples of research in which hydroeconomic models have been used to analyze institutional changes can be found in studies by Booker and Young (1994), Brouwer (2000), Characklis et al. (1999), and Fisher et al. (2002).

By showing the significant economic advantages of water reallocation based on market principles, and simultaneously showing the ability to effect such market reallocations within the existing hydrologic structure, hydroeconomic models have significantly contributed to the

introduction of market mechanisms for water allocation in the US. In addition, the effect of markets on groundwater use has been addressed by Knapp et al. (2003), and on water quality and saline return flows by Leftkoff and Gorelick (1990). Hydroeconomic models have also played an important role in the analysis of the impact of water markets in Australia: Connor et al. (2010).

4.2.4 Static Spatial Models

One of the first static inter-basin hydroeconomic water models was by Vaux & Howitt (1984). The authors defined a spatially connected series of basins in California, each with its particular derived demand for water, capacity for moving water between regions, and cost and supply functions. The optimized allocation of water generated by this model foreshadowed future water market transactions between Imperial Valley and the Los Angeles urban water users. Significant extensions of the basic idea of spatial equilibrium in hydroeconomic models has been made by Booker and Young (1994), Cai et al. (2003) and Ward and Lynch (1996). Most hydroeconomic models only consider the direct use of water in the objective function. However, increasingly policymakers and environmental interest groups want to measure the change in instream flows and identify gains from trading instream flows for consumptive uses. The addition of instream flow values can fundamentally alter efficient allocation as shown by Booker & Young (1994), Colby (1990) and Griffen and Hsu (1993). Lee et al. (1994) show the importance of modeling the flows in the upper and lower basins of the Colorado River. Hydroeconomic models have been extended in several other dimensions. The addition of explicit modeling of groundwater resources within the context of a large spatial model can be found in Harou and Lund (2010) and McCarl et al. (1999). Booker (1995), Characklis et al. (2006), Ward et al. (2007) and Sheng et al. (2005) focus on extreme events in the common form of drought and flood response impacts, and the ability to offset these impacts using a portfolio approach. Lund and Israel (1995) and many other researchers analyze the value of potential water transfers using spatially explicit models.

4.2.5 Stochastic Dynamic Approaches to Hydroeconomic Models

The first formal stochastic dynamic economic model applied to water allocation was published by Burt in 1964. This paper addressed the optimal allocation of groundwater over time. A classic paper, this was essentially the foundation of a large number of other papers in which the equations of motion are represented by discrete stages and states and the problem is solved by classic backwards solution of stochastic dynamic programming applying Bellman's principle. This application and all other empirical applications using this approach are restricted in the number of states they can use to realistically represent a groundwater basin by the ever present curse of dimensionality. Several ingenious ways have been used to reduce the curse, such as those used by Provencher and Burt (1994) and Woodward, et al. (2005). Some examples of how the economic models of applying analytic control theory directly to the economic allocation of groundwater were published by Noel et al. (1980) and Noel and Howitt (1982). Two alternative methods to the traditional backwards solution can be characterized as nested optimization methods such as developed by Draper et al. (2003). An alternative solution that relies on steady-state properties of economic dynamic optimization problems have been demonstrated by Howitt et al. (2001). These methods rely on polynomial approximations to the current state value function of the stock of water when it reaches steady-state. The steady-state properties can then

be used to provide approximate solution methods and transitory problems that have terminal value functions.

An essential dividing characteristic of dynamic models is the way in which expectations about future water flows or stocks are characterized. Many models do not formally model stochastic hydrology but use representative samples of hydrology over long time periods to characterize the stochastic nature of water supplies in storage. In control theory parlance these models can be characterized as open-loop models in which the information update in observed realizations of the uncertain state is not used to modify future controls. There is a small set of closed-loop models in which the information gained is explicitly used to update future controls. A simulation approach such as used by Bredehoeft and Young (1970) is also used to estimate optimal intertemporal allocation of groundwater. The Calvin model developed by Jenkins and Lund (2000) and subsequent publications, combines a very wide range of spatial specificity with a long time series (over 70 years) of dynamic hydrologic record, to provide a practical policy analysis tool that can cover stochastic dynamics and spatial details.

Risk has been the explicit focus in a number of hydroeconomic models. For example, risk in agricultural production decisions to mitigate impacts of shortfalls in water treaty deliveries are addressed by Robinson, Michelsen and Gollehon (2010).

The division between spatial and dynamic models rests on how the foresight or expectations on water supplies is treated. The steady state models discussed above essentially take an expected value, and then usually test for sensitivity to the ranges of supply values around the expected value. Dynamic economic models have a broad division between those that explicitly model the dynamic economic process, and those that impose dynamic hydrology on a static economic process. The distinction will be drawn in the next section.

4.2.6 The Solution and Calibration of Hydroeconomic Models

Linear programs are the standard solution algorithm used to optimize most hydroeconomic models. The large size of hydroeconomic models is usually due to their detailed spatial specifications and the use of long hydrologic time series to characterize the stochastic nature of water supplies. The resulting models often have tens of thousands of dimensions, which gives the Simplex solution method used in linear programming an inherent advantage. In many cases the nonlinearity that is inherent in the response to water, hydropower, or environmental production functions can be approximated by a stepwise linear approach.

While the solution of large linear programming models is straightforward, their calibration is not, especially in the absence of true market prices, or reliable primary data on water use and return flows. Linear programming models have to be calibrated by complex sets of linear inequality constraints which then leads to rigidities in terms of their ability to respond to policy scenarios. In addition, a common approach to calibrating hydrologic components is to adjust either the return flows or the consumptive use at each individual node to ensure hydrologic balance. The economic component of hydroeconomic models also presents calibration problems in terms of deriving the supply function inherent in optimal water use. A widely used approach to calibrate optimizing economic models is the positive programming approach discussed in section 2.1

(Howitt 1995). This method uses observed allocations of economic inputs to infer the marginal cost conditions, and thus integrate these into empirically consistent marginal cost functions. A similar approach has been taken by Cai and Wang (2006) to the calibration of hydrologic models. In this approach Cai and Wang calibrate penalty functions based on return flows and consumptive water use at each node in the hydrologic model. The approach works well, but is computationally intensive even with modern nonlinear algorithms. With advances in both calibration methods and algorithms, it seems likely that many hydroeconomic models will have significant nonlinear components in the future.

4.3 Applications to modeling surface supply

Provision of water supply to support new uses has traditionally focused on structural approaches dominated by new surface water storage and new conveyance facilities. Today a range of circumstances prevail world wide, and water development takes a very wide range of forms. Similarly, water modeling in support of new water demand today addresses this increasingly large range of circumstances.

Most work in the developed nations has focused on mature water economies where the opportunity costs of physically developing new supplies exceeds the benefits of at least some existing uses, and the problem of providing water for new uses is one of reallocating water from existing uses (Randall, 1981). Howe, Lazo, and Weber (1990) illustrate the economic impacts of reallocations on a regional rural population, while Boehlert and Jaeger (2010) model drought impacts in the Klamath River Basin of Oregon and California when agricultural and environmental uses compete for scarce water supplies. But while a mature water economy characterizes water development in arid and semi-arid regions of the developed economies, in the many other regions construction of physical structures to support new uses are viewed as a critical aspect of water development. Moreover, technological advances in desalination of seawater and brackish groundwater point modelers to include both reallocation and physical supply backstops in modeling efforts.

Chang and Griffin (1992) capture clearly the fundamental economic modeling used to address water supply and allocation in mature water economies. In practice, this typically means identifying the lowest cost opportunities for agricultural to municipal transfers. They identify not only the opportunities, but the practice of reallocation along the course of the Lower Rio Grande Valley in the U.S. The modeling environment is simple, though information requirements are complex. They rely on basic budgeting practices, and identify traditional linear programming practices for modeling irrigation demands. Importantly, they pay particular attention to the timing of municipal water demand, and the timing of the existing agricultural water uses.

Economic modeling of surface supply with highly simplified hydrologic and institutional frameworks are used when fundamental characteristics are difficult to clearly address in more complex models. For example, important economies of scale are typically present in water delivery, leading to questions on the efficiency of market power. Chakravorty et al. (2009) use a static model to consider market power when distribution losses are prevalent and generation and end-use markets also exist.

Often temporal management of surface supplies captured in reservoir storage is included in the economic modeling problem. In many cases several alternative supply sources may be available, very frequently including groundwater. In addition to appropriate treatment of the alternative supply sources, simple hydrologic modeling of surface-groundwater interactions may also be necessary in some of these cases. Finally, economic modeling of surface supply increasingly requires consideration of projected availability under alternative climate change scenarios. Much of the work on economic modeling of surface water supply thus occurs in complex hydrologic environments, and is increasingly addressed using explicitly integrated hydroeconomic modeling approaches.

The basic economic problem of using surface storage to reallocate surface supplies over time is often included within such integrated modeling environments. A review of the essential strategies for economic and optimization modeling of reservoir management is provided by Celeste and Billib (2009) and Rani and Morreira (2010). Research on reservoir management in relatively simple systems ranges from that advancing the economic foundations for reservoir operations rules (You and Cai, 2008), to modeling explicitly addressing the tradeoff between reliability and mean levels of water use when evaporative or other losses are important (Booker and O'Neill, 2006).

4.4 Applications to Economic Modeling of Ground Water Management Issues

Ground water deposits, or aquifers, supply much of the world's fresh water withdrawals, for agriculture, industry and for households. After the mid-twentieth century, rapid technological improvements in pumping and water distribution technologies, combined with relatively low energy costs led to extensive ground water development throughout the world.

Ground water is a classic “common pool” resource--defined (Ostrom 2010) as one with a high degree of subtractibility (whatever one individual consumes cannot be consumed by others) together with high costs of establishing and enforcing property rights and exclusion of potential beneficiaries. Absence of property rights (“open access”) in ground water frequently led to over-exploitation--withdrawals exceeding natural replenishment. Overdrawn aquifers are most often exploited under open access rules by numerous individually-owned farm pumps located on the surface portions with agriculturally-suitable soils and topography. In consequence, adverse effects (external costs)--such as over-rapid depletion of ground water stocks, higher pumping costs, intrusion of lower-quality waters such as sea water, depletion of hydraulically-linked river flows and subsidence of over-lying lands--have occurred. Economists soon hypothesized a need for regulation of ground water extraction and to develop empirical models to analyze such hypotheses.

4.4.1 Regulation of ground water withdrawals

A major strand of the ground water economics modeling literature addressed the question of whether and how to regulate ground water withdrawals. Ground water hydrologists and engineers often recommend a “safe yield” rule, which essentially limits the withdrawal to the rate of natural recharge, keeping the aquifer stock intact. Economists, in contrast, recognized the

reality for many aquifers that extraction rates already greatly exceeded recharge, in effect, mining the stocks. Economists treated aquifer stocks as non-renewable resources. The optimal rate of use of an exhaustible resource is determined by considerations of current costs and revenues, but also with reference to the future profit foregone by a decision to extract a unit of the resource at present (e.g. Scott, 1967). In an open access regime, users tend to ignore the future value of the resource, thus mining it at a too-rapid rate.

Early ground water modelers focused on the optimal rate of extraction, drawing on the theory of the mine to conceptualize the potential temporal resource mis-allocation problem and show directions toward optimal allocation. Kelso (1961) was probably the first to attempt an empirical model of the issue, estimating with desk calculations the foregone future value for a central Arizona agriculture case. Adapting the then-new technique of dynamic programming with computers to a central California region, O.R. Burt produced a remarkable series of papers (e.g. 1967, discussed above) which, extending the theory of the mine to the case where resource stocks were partially renewed by a stochastic process, derived decision rules for optimal temporal allocation of ground water.

In several papers, Gisser and Sanchez (1980) applied dynamic optimization methods to various regional aquifers in the southwestern U.S., concluding (in e.g. 1980) that the gains from socially optimal allocation over time compared to non-intervention would be small to negligible. A number of subsequent studies did not contradict these surprising and disturbing conclusions. Koundouri (2004a) analyzed the type of dynamic aquifer-economic model used in the previous literature, showing that the rate of interest, the elasticity of water demand and hydrologic considerations would be important factors influencing the optimal degree of regulation. A few analyses extended the simple “single-cell” aquifer model used by most ground water economics modelers to circumvent the conceptual, data, and high computer cost challenges posed by realistic modeling of dynamic hydrologic and economic systems. The single-cell approach (which hydrologists call—with derisive intent—a “bathtub model”) assumes the aquifer responds instantly and uniformly over its extent to pumping. Depth to water and hence pumping costs are everywhere identical. Bredehoeft and Young (1970) formulated the problem as a simulation with multiple connected aquifer cells, solving the simulation repeatedly for varying policy instruments (taxes or pumping quotas). They reported an increase in present value of over \$US300 (2010 prices) per acre for the highest-valued quota policy, not an insignificant gain. However, in common with the rest of the literature, the corresponding costs of regulation were not studied. (See Koundouri (2004b) for a discussion of the problems of managing ground water.) Recently, Brozovic, et al. (2010), using spatially explicit dynamic ground water flow equations, show that for small confined aquifers, single cell models provide a reasonable approximation. For larger confined aquifers (thousands of square miles—such as the much-studied Ogallala-High Plains Aquifer in the west-central United States), single-cell models are shown to seriously underestimate the magnitude and spatial nature of the groundwater externality.

Another strand of the literature addressed the problem of optimal conjunctive use of ground and surface water where both water sources are important. Noel and Howitt (1982), Provencher and Burt (1994), Knapp and Olsen (1995), (all dealing with California cases) represent significant contributions to this literature. Young et al.(1985) developed a hydrologic-economic-institutional

simulation designed to analyze policy responses to a pumping externality on surface flows of a Colorado stream/tributary aquifer system. Tsur (1991) and Graham-Tomasi (1995) showed for an Israeli case that ground water could yield a significant value as a buffer stock in the presence of significant risks of low surface water flows due to drought. Knapp et al. (2003) consider the effect of declining water quality in a regional conjunctive ground and surface water supply context. et al.

Another interesting direction was taken by Roumasset and Wada (2011), who modeled the optimal management of a Hawaiian coastal aquifer where excess withdrawals can lead to seawater intrusion and aquifer destruction, where recycling of wastewater is a supply option, and where desalination of seawater is the backup supply.

4.5 Other Applications

4.5.1. New Supply Sources

In contrast to work in mature water economies where regional opportunities for physically increasing supplies are limited, much of the developing world has a rather limited water supply infrastructure. The result is that in practice the era of large dam and infrastructure construction is hardly passed (e.g. Three Gorges in China). Briscoe (2010) argues that much research in water resources management (particularly in the U.S.) fails to include development of new water supplies as an explicit alternative and is thus “increasingly parochial” and blind to the differing stages of infrastructure development in many middle and low income nations. In economic modeling work addressing both mature and expansionary water economies, he sees the work and lessons learned in Australia, Chile, Brazil, and Mexico as being increasingly relevant and influential. Work which integrates consideration of new supply alternatives with demand management alternatives in mature water economies is needed to provide long run policy guidance. For example, where development of new surface supplies from existing freshwater resources is not an option, desalination is increasingly suggested as a possible new supply source. This is the approach taken by El Paso Water Utilities in Texas which is developing new freshwater supplies by means such as construction of the largest inland desalination plant in the world, utilizing brackish groundwater to meet growing and projected demand. In the 50 year State Water Plan, this was determined to be the most cost-effective source following extensive conservation measures and water reuse (Texas Water Development Board 2011). But recent work suggests caution in generalizing this result (Becker, Lavee, and Katz, 2010), as costs remain problematic relative to opportunities from adoption of conservation techniques and other demand management approaches.

4.5.2 Climate and Sustainability

Economic modeling also addresses questions of the adequacy and sustainability of water supply sources under changes in climate. Early work relied upon simple tabulations of surface water use and agricultural production to estimate impacts of projected changes in water resource availability due to climate change (e.g. Frederick and Gleick, 1990). Many examples of recent work addressing the impact of climate change on water supplies make use of the optimization

approaches discussed elsewhere in this review (e.g. Adams et al. 1999; Tanaka et al., 2006; Rosegrant et al, 2000; Ward and Lynch, 1996; and Zhu et al, 2007. The sustainability of water supplies and systems is modeled by Cai et al. (2003) and Harou & Lund (2010).

Also, numerous studies have employed a form of the hedonic (inductive) method-- sometimes termed “Ricardian” analysis--to address climate change issues, particularly as to the role of agricultural crop irrigation in responding to climatic variation. The Ricardian model uses cross-sectional data to analyze the effects of local climate, land quality and sometimes irrigation on land values or net farm incomes. The results then are used to infer the effects of climate change on agricultural output and incomes. Schlenker et al (2005) is a recent rigorous example of Ricardian studies of the role of climate and irrigation on agriculture in the US. Mendelsohn and Dinar (2009) survey the literature and summarize World Bank-sponsored Ricardian studies of twenty-two countries on four continents.

In addition, economic modeling of water resources is used to address a number of related issues. For example, flood economic impact models consider risk and incentives under alternative policies (e.g. levee protection, expanded insurance markets, and flood plain zoning). Economic impact and policy analysis of dam removal typically requires modeling of related power markets, and explicit consideration of environmental benefits.

4.5.3 Economic Costs and Risks of Floods

Extreme water supply events, particularly floods, pose special difficulties for water policy modelers. Measurement of the benefits of flood hazard reduction assumes rational fully informed floodplain residents would be willing to pay up to the present discounted expected (probability-weighted) value of their losses to avoid such losses. Evaluation of flood alleviation projects and policies is location-specific, depending on the hydrologic conditions and the nature and density of present and prospective human activity on the floodplain. The wide variety of actual and potential economic activities found on floodplains—residential, industrial, commercial, agricultural, environmental—makes this a formidable task. Most frequently used is a deductive approach called the *property damages avoided* method, which forecasts the future expected activities, structures and land uses in the floodplain and compares future flood damages *with* versus *without* the proposed policy intervention (for example, Sheng et al. 2005). Academic writings on this subject are limited in the US, but less-so in Europe. Although non-market--both revealed preference and stated preference—techniques have been attempted, a major obstacle is the reality that floodplain users and residents are unlikely to have an accurate understanding of the probabilities of experiencing flood damages.

Economic analysis of potential flood risk depends on whether the project is exclusively dedicated to mitigating flood risk, or more commonly, the flood risk is integrated with a water supply project. Flood risk is defined as the probability of flooding multiplied by the cost of damage that will occur with a flood. In all of situations management and structural actions cannot, and should not, reduce the risk to zero, so a residual risk remains which should be internalized by flood insurance policies. In many situations and agency publications, flood risk is defined in terms of flood frequency usually expressed in hundred-year floods or 500-year floods.

The US Army Corps of Engineers National Economic Development Manual (2010) describes the current federal approach to applied estimation of flood damages avoided. Researchers at the Flood Hazard Research Centre at Middlesex University (UK) have over many years developed and refined methods widely used in the UK. See Penning-Rowsell et al. (2010) for a recent user-friendly statement of principles and applications.

It has been recently recognized that, like water supply models, flood management models have both a technical and a behavioral component. Early models of flood management emphasized the technical component, but more recent models such as Galloway (2009), and Suddeth et al. (2010) have demonstrated the value of the integration of the behavioral aspects with the technical engineering aspects of the model.

For example, in some cases a policy may result in an improvement in the technical flood frequency rating of an area. This would change the standards for the national flood insurance program, which in turn, can result in a rational behavioral response that increases urban development in the floodplain and thus increase total flood risk in economic terms. In this example an improvement in the technical capacity without controls on the behavioral response of floodplain residents would result in an increase in the economic flood risk. Another trade-off that can be modeled by economic engineering models of flood risk (Zhu and Lund, 2009) is between levies that contain floods in the river bed versus floodplains which dissipate the energy over a much larger space.

It seems likely that the current trend will be to integrate both the technical and behavioral aspects of flood management into regional integrated water resource management models.

4.5.4 Regional Economic Impacts Development

Water policy is concerned with more than the microeconomic impact of water allocations. In many cases water allocations directly affect the local and state economy, and politicians are more likely to respond to changes in employment and regional economies than they are the net returns of small groups of farmers. Thus the impact of hydroeconomic models is greatly enhanced if they can be linked with regional economic models using CGE or input output methods. Many authors have linked input output models to hydroeconomic models using the change in gross value of output in the farm sector or in industrial sectors to drive changes in the input output model, usually using simple impact multipliers for employment and regional economic activity. For example, Taylor and Young (1995) and Howe and Goemans (2003) represent alternative approaches to this issue for water transferred from agriculture to higher-valued urban and/or environmental demands in similar eastern Colorado regions. The former study applies a stochastic programming model to measure foregone direct economic *benefits*, while the latter derives foregone direct plus secondary economic *impacts* via a Leontief-type regional model. (The precise distinctions between impacts and benefits in regional economic modeling remain to be clarified.)

Hydroeconomic models have also been linked with CGE models that are able to show not only the regional economic effects, but the full adjustment of spatial trade. Some examples can be found at differing scales of economic impact in Berck et al.(1991), Tsur et al.(2004), McKinney et al.(1999). In some CGE and input output models, the water based economic sector is directly

embedded in the model by defining a few economic sectors that correspond to agricultural production and industrial water use. In most cases, these models are unable to reproduce sufficient hydrologic complexity for realistic policies, and usually suffer from other aggregation of economic sectors as well. Thus the most promising avenue for future development is in the formal linkage of regional economic models to hydroeconomic models. This combination of models will have the advantage of realistic specifications of the hydroeconomic sector coupled with the ability to measure the more general impacts on the economy as a whole.

4.5.5 Game Theoretic Models of Groundwater Use

Most specifications of economic models of optimal use of groundwater over time range from the collective social optimal objective function, to the other extreme of private individual maximizing actions that often lead overexploitation of aquifers. The first alternative to these polar extremes in the form of a game theoretic specification was proposed by Negri (1989) in a classic paper that characterized groundwater extraction behavior between individuals as a differential game. In this paper, Negri showed that rational groundwater users would consider the option of strategic behavior as an influence on their optimal pumping actions. This more realistic specification allows for the knowledge of the depth and quantity at which neighboring pumpers are operating to affect the rate of extraction of other individuals. Rubio and Casino (2002) also showing that strategic behavior amongst pumpers is an additional source of common property groundwater inefficiency. While these models have an intuitive appeal in terms of likely behavior, like many game theoretic specifications, they present considerable difficulties in their empirical implementation. Subsequent studies using economic experiments have confirmed the existence and cost of strategic behavior in common pool extraction problems.

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4.6 Future Trends and Advances in Hydroeconomic Models

With their complicated specification and inherent nonlinear and stochastic form, hydroeconomic models are natural beneficiaries of the ongoing advances in genetic and neurological based algorithms. Such algorithms shows significant promise but have not been widely applied to hydroeconomic modeling. This class of algorithms is particularly promising for solving dynamic stochastic problems that have proved intractable for the large dimensions of most hydro-

economic models. One exception to the absence of genetic algorithms is the paper by Cai and Wang (2006).

A second area which will lead to significant advances in hydro-economic modeling is in the ability to reconstruct both hydrological and economic relationships for remotely sensed data. The collection of detailed data in the form of six different spectral signatures for 30 m² pixels by the Landsat satellite has been ongoing for many years. The advances in recent years have been in terms of the algorithms able to interpret this detailed data, and also the GIS developments that make it accessible to the modelers. For example, there are now several algorithms available which are able to estimate both evapotranspiration (ET) and dry matter production by pixel area by month. One example is the Sebal algorithm (Bastiaanssen, 2005) that has been extensively tested against physical measures of ET. When combined with large data set estimation methods, this new source of physical data can provide a valuable basis for estimating economic behavior. It can also form the basis of real-time water markets, and markets for seasonal conservation, which were not feasible without a cheap and timely method of measuring ET. The third area of development of hydroeconomic models is in the integration both downward to more complex hydrologic models and upward to more general regional and national economic models. Both of these trends will strengthen the knowledge needed for better integrated water resource management.

5. Governance, Institutions, and Compact Design

Water's physical characteristics make it difficult to capture and contain and measure, and its availability varies greatly over time. Water delivery frequently involves capital intensive infrastructure with such great economies of scale that investment capital far beyond the means of individual water users is suggested. As a consequence, myriad positive and negative externalities are present in the provision and use of water. Finally, due to its central significance in supporting life directly and indirectly through irrigated food production, water use takes on a cultural significance which cannot be discounted. Together, these factors lead to water governance which typically makes little use of traditional market institutions such as transferrable private property, and limited use of water markets to allocate rights to water resource use. Instead, water is allocated by factors related to location (e.g. riparian water rights for property owners adjacent or near water flows), or by rights gained through negotiation (e.g. interstate compacts), by appropriation (e.g. prior appropriation in much of the western U.S.), or by contract with a governmental authority (e.g. shares in federally funded irrigation projects, which themselves typically have rights defined by prior appropriation).

A central question in the economic modeling of water resources becomes the evaluation of the allocative efficiency of existing and hypothetical alternative institutions for water resource governance. Because opportunity costs to water users are often very low with existing institutions, but marginal cost of supply augmentation is frequently high, substantial incentives to overuse water are common. Economic modeling is used to address the welfare benefits which might accrue through simple reallocations, or by introducing incentive compatible institutions. Frequently these include pricing which more directly reflects marginal costs, introduction of (limited) water markets which increase opportunity costs of water use, or removal of market

distorting subsidies. Care must be taken with approaches which require volumetric measurements of water diversions and use however: while such measurement seems fundamental, it can in practice create a range of perverse incentives, or simply be an impossibility under existing conditions.

Starting from a focus on local allocation, Burness and Quirk (1979) explored the difficulties in establishing a system of allocatively efficient water rights in the absence of transferrable property rights, defining in the process the fundamental inefficiencies to be expected with riparian and appropriative water allocation institutions. Moving from local water source to the regional and international scale, compacts and treaties establish rights and obligations between water using states, provinces, and nations. While formal economic analysis of compact and treaty design and structure has received relatively little attention, the fundamentally appropriative language present in typical agreements suggests that proper incentives are lacking for efficient water use between parties. Bennett, Howe, and Shope (2000) consider this problem, and derive conditions for “universally optimal” compact design.

Considerable attention has focused on the use of water prices which reflect opportunity costs. Most typically, water charges are levied on users to recover some combination of operating and past capital costs. Rarely are prices used to ration the existing deliverable supply among water users. More commonly, in times of water shortage use is allocated by either a priority system, or proportional sharing of shortfalls, with pricing playing only a minor role. Using a linear programming model of irrigator behavior, Gardner and Young (1988) provide one example of how direct pricing of delivered water, or subsidies for water saving technologies, can be used to improve welfare through changes in irrigator behavior.

In addition to approaches which move towards prices which reflect opportunity costs, economists have long suggested that market institutions such as water rights transfers and water banks have the potential to increase economic efficiency relative to traditional water allocation institutions (e.g. Gardner and Miller). Potential welfare improvements from market allocation mechanisms are also identified in the developing world (Rosegrant and Binswanger, 1994).

Complementing economic modeling focused on evaluating permanent water rights transfers, the role of water marketing on an annual or shorter run basis has received substantial attention. For example, Charaklis, Griffin, and Bedient (1999) use a simple static optimization to explore potential benefits of leasing between municipal water rights owners and agricultural users in the Lower Rio Grande Basin in Texas. They demonstrate that in the case where municipal water users have made precautionary water rights purchases in excess of current needs under typical hydrologic conditions, leases to agricultural users can generate substantial increases in regional well-being. Benefits of proposed short-term water markets between off-stream and instream users were directly estimated by Whittlesey, Hamilton, and Halverson (1989) from optimization modeling of irrigator response to an interruptible water source. Leftkoff and Gorelick (1990) model the use of a hypothetical water rental market between irrigators where water quality is a concern and ground and surface water is linked in an alluvial system. They find that an annual rental market can increase profits for market participants, while lowering groundwater salinity. Griffin and Hsu (1993) demonstrate that, more generally, it is possible to incorporate instream

flow values into market and other incentive based institutions in order to achieve efficient allocations.

Such work suggests potential gains from water pricing, water banking and related market institutions in response to growing urban and environmental demands during drought. Michelsen and Young (1993) formalized the conditions under which a particular type of market contract, water options, would be preferred to permanent water transfers. Generalizing from their modeling of a case study, they conclude that “dry year options are an economically viable approach under a wide range of economic conditions” (p. 1019). An application by Lund and Israel (1995) explores the use of dry-year options and spot market transfers to provision of urban water supplies in California, by employing multistage linear programming to identify least cost opportunities. Byrnes et al (2010) represents the most recent of several Australian applications of the option contract model, in this case to the Murrumbidgee River Valley where both urban (from the Australian Capital Territory - ACT) or environmental demands during droughts might be significant.

While considerable attention has focused on identifying potential applications of water marketing and water banking, the actual number of implemented water marketing and water banking institutions has been rather limited. Further, in cases where market mechanisms exist, the number of transactions may be smaller than what might be expected. Young (1986) explores alternative hypotheses, considering both economic and noneconomic factors to help explain the surprisingly limited number of observed water transactions.

But robust and active markets are observed in particular contexts, and economic modeling of those markets has substantially increased our understanding of real world market based water allocation institutions. An early (and ongoing) formal water market in the state of Colorado is in shares of water from an interbasin transfer project, the Colorado-Big Thompson Project (CBT). Gardner and Miller (1983), using an asset pricing model, found that while most CBT shares at that time were held by agricultural users, prices fully reflected expected values to future municipal and industrial buyers. In recent work regarding an extensively studied Australian basin with active water markets, Turrall et al.(2005) conclude that while permanent water transfers and reallocations appear limited, the existing market satisfies a number of Howe et al’s (1986) criteria for well-functioning markets.

6. Conclusions and Future Directions

Water resources and policies in much of the world have gone from expansionary development of additional water supplies to a mature phase where existing water resources are scarce, water is a commodity and there is competition for water across different uses. Contributing to the scarcity and competition for water are the growth in population and economies and changes in environmental values and associated water demands. Changes and uncertainty in climate and hydrologic conditions have exacerbated scarcity and the increasing competition for water. In response to these changes, economic modeling of water resources has evolved from modeling individual sector use, usually independently of other water demands, and water supplies at local spatial scales, to integrated water demand and surface and ground water resources at larger

watershed, river basin and even inter-basin scales. Two other major changes are the inclusion of environmental water values and water governance institutions. Supporting these changes, hydro-economic modeling over the last twenty-five years has advanced in theory, model design, and computational techniques. These changes have resulted in a much improved and greater capacity to understand the effects of water resource policies.

Most of this paper's focus has been on the evolution of hydro-economic models under water scarcity conditions in a mature water economy. It is important to recognize that some areas of the world are still in the expansionary phase of water supply development. These regions have the opportunity to learn and benefit from the knowledge that water development and management actions have multiple, interdependent effects. Identifying and considering these interactions using integrated hydro-economic models in the development phase could result in both immediate and long-term benefits for water and other resources and avoid the problems and consequences of ignoring important interdependencies and impacts.

The changing conditions contributing to and increasing water scarcity and trends in economic modeling of water resources discussed above will continue. To address these changes, both the depth and breadth of economic modeling of water resources are anticipated to expand in the future. The development of better and more detailed economic and hydrologic information will enable increased depth and accuracy of hydroeconomic models and expanded interdisciplinary integration of other physical and social sciences will allow these models to be applied to address a growing number of issues. An important area of future hydroeconomic model development will be the expansion of models to understand and address transboundary water resource economic, hydrologic, environmental and institutional policies and interdependencies.

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