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Decision support for water policy: a review of economic concepts and tools

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Abstract

This article reviews research on the application of economic concepts and tools to the analysis of the preservation, conservation, development, consumption, supply and allocation of water resources. It summarizes research on economic analysis to support policy formulation, implementation and evaluation, including both project appraisal and the design of institutions. Economic analysis can support *ex post* analysis of existing mechanisms that influence the allocation of water: Such mechanisms include laws, regulations, supply management, demand management, population and climate change. Economic analysis can also be used to conduct *ex ante* analysis to design future water allocation institutions. These institutions include various forms of marginal cost pricing, valuation of water in alternative uses, water quality management, optimization models, integrated supply and demand management, transboundary management, virtual water, decentralized management, common property institutions and watershed councils.

Keywords: Economic analysis; Institutions; Models; Policy design; Water resources

1. Background

Water resources managers and policymakers worldwide are faced with increasing and competing demands on a limited and more uncertain resource as populations grow and climate varies. Water problems cover a variety of areas, including depletion of aquifers, contamination of ground water, siltation of dams, salinization of irrigation water, prolonged drought and flooding. The search for sustainable water policies is high on the international and national agendas (Lundqvist, 1998; Gleick, 2000). For example, the year 2000 Water Framework Directive is the most important European Union directive in the water field in several decades. The Directive requires "good water status" for all

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European waters by 2015 (Garin *et al.*, 2002; Logan & Furse, 2002; Mostert, 2003; Borja *et al.*, 2004; Achleitner *et al.*, 2005; Stelzer *et al.*, 2005).

By 2050 some 40% of the world's population will probably experience water shortages (Gadgil, 1998; Kuylenstierna *et al.*, 1998; United Nations, 2002; Hamdy *et al.*, 2003). Poor people spend a high proportion of their time, income and other resources securing water to meet their basic needs. A growing scarcity and competition for water, in quantity, quality and location threatens advances in poverty eradication, public health and food production. Poverty persists in water scarce areas. The effects of pollution and overexploitation of groundwater aquifers have disproportionate impact on the poor and socially vulnerable. A continuing challenge faced by water resource managers is to identify the impacts and tradeoffs of current water-related decisions over many future time periods (Loucks, 2000; Semiat, 2000; Postel *et al.*, 2001). Economic concepts and tools have the potential to inform the choice among numerous potential methods of improving the quantity and reliability of water supply as well as the choices for eliminating water resource deficits (Batabyal, 2001; Tsur *et al.*, 2004).

Overall, a significant challenge for 21st century water policy is to satisfy growing human demands for water while protecting the aquatic ecosystems upon which economies and life itself depend. Especially in dry places with rapidly growing populations and economies, this task is daunting (Postel *et al.*, 1998). Economic analysis plays a role in addressing the ancient water management challenges, such as the best methods to cope with hydrologic extremes like floods and droughts (Kundzewicz, 2002). It also communicates 21st century values where society's important water decisions are increasingly made through interaction between governments, civil society organizations and professionals (Biswas, 1999, 2001; Lundqvist, 2000).

Economic analysis of measures such as demand management and market transfers hold the potential to mediate conflicts in trans-boundary waters (Giordano *et al.*, 2002). With more than 200 international rivers in the world and decreasing per capita water supply, the use of economic principles to support successful resolution of international water conflicts will be an increasingly important step in promoting economically efficient water development and use (Giordano *et al.*, 2005; Young, 2005). A water problem exists when water is not found in the desired quantity and quality at the right place and time.

Controversy continues to surround water decisions everywhere, particularly where emerging uses such as proposed preservation or restoration of a natural environment or ecosystem compete directly with more established uses such as agriculture, hydropower production and city water supply (Varis & Fraboulet-Jussila, 2002). Non-specialists may be overwhelmed by the wide range of benefits and costs that are claimed for various water policy proposals. Yet better understanding can be obtained only by consulting lengthy sources requiring considerable background in economic analysis (e.g. Varian, 1992). Few published works are available that distill the wide scope of modern economic concepts and tools that could be used to support emerging 21st century water management and policy decisions.

Therefore, the objective of this paper is to support a framework for handling these issues by reviewing modern economic analysis as it relates to the conduct of water policy decisions. Section 2 identifies selected water management objectives. Section 3 reviews economic concepts and tools that can support *ex post* analysis of mechanisms that influence the allocation of water. Section 4 examines the role of economic analysis in supporting *ex ante* analysis to design future water allocation institutions. Section 5 concludes with a summary of emerging research challenges.

2. Water policy objectives

The objectives of water resource policy serve as standards for judging the effectiveness of institutions for allocating water (Porto & Porto, 2002). Examples of such institutions range from complete government control, to a mix of market and government allocation, to market allocation with background government support. Institutions that influence the allocation of water within any community are its unique system of rules for sharing available water among known sources of demand.

2.1. Economic efficiency

Allocation of water among users can be judged from the view of economic efficiency, where water allocations are part of a series of investment projects (Cai *et al.*, 2003). Water is the scarce resource and the economic sectors use the resource and produce economic returns. In an economically efficient water allocation, the marginal benefit from the use of the water is equal across uses in order to maximize total benefits produced by the water (Yang & Weersink, 2004; Young, 2005). For economic efficiency to occur, the benefit from using one additional unit of the water by one user should be the same for all users. If not, society benefits by allocating more water to the sector, user, or use for which the incremental benefits are highest (Brookshire *et al.*, 2002). The economic and policy challenge posed by water scarcity is to allocate a known supply of water among all competing users. Where water is a renewable resource, produced mostly by current rain or snow, a major challenge is to allocate the current period's flow between competing users (Payne *et al.*, 2004). However, water is sometimes a depletable resource that is used by drawing down on a fixed stock, such as pumping from a non-rechargeable aquifer (Howe, 2002). In this case, the challenge is to allocate water among competing users in each of many time periods.

An economically efficient allocation of the current period's water flows (often surface water) needs (1) to account for many competing users and (2) must deal with highly variable flows among periods. The first issue is important because many users typically claim a legal right to use the water (Nieuwoudt & Armitage, 2004). These users include groups like farmers, cities and factories that consume water by taking it from rivers and streams. Recreational users and environmental uses produce direct benefits while the water resides in streams or reservoirs. The second issue is important because streamflows vary widely over days, months and years, so the total supply changes from one time to the next, sometimes unpredictably (Payne *et al.*, 2004). Economic efficiency is achieved if the equi-marginal rule is followed:

$$\mathrm{MNB}_1 = \mathrm{MNB}_2 = \ldots = \mathrm{MNB}_n \qquad (1)$$

Marginal net benefits are equal for all competing uses. When enough water is transferred so that marginal net benefits are equalized among all users, it is not possible to increase overall total net benefits by more transfers (Cai *et al.*, 2003; Bereciartua, 2005). Consider the effects of falling supplies, as might be seen in a drought (Lemos *et al.*, 2002). The equi-marginal rule still works and is still required to produce economic efficiency. In fact, that rule defines a very special method for sharing shortages produced by supply shortfalls. It says that the loss in total net benefits produced by a drought is minimized if the more price-elastic user, typically agriculture, gives up a higher proportion of its use. As total supplies fall, the marginal net benefit displaced (opportunity cost) from losses to the more price-inelastic user, for example, municipal and industrial (M&I) uses, is higher than equal quantities lost from agricultural use. To minimize total economic damages produced by a drought, a larger part of the shortfall is typically placed on agriculture than on cities (Salman & Al-Karablieh, 2004). Because economically efficient methods for coping with supply shortages require unequal shortfall sharing patterns, any rule of thumb for sharing shortages, such as proportional sharing of shortfalls, is unlikely to produce economic efficiency. However, well-designed market institutions like water banks or water rental markets may be able to compensate for economically inefficient shortfall-sharing measures, as pointed out recently by private water developer Boone Pickens (Pickens, 2004).

Sometimes water supply is a stock and not a flow (Wolfe & Brooks, 2003). That is, supply is not continually renewed but is a non-renewed, fixed supply whose current use takes away from future use. Two good examples are non-recharging aquifers and non-recharging natural lakes. Extending the analysis of economic efficiency to account for depletable water stocks requires that the depletable nature of the resource be considered. When demand exceeds recharge for a particular supply source, the resource is mined just like a seam of coal or vein of copper. The mining continues until the supply is depleted or the marginal cost of supply becomes economically prohibitive. A similar equi-marginal rule guarantees economic efficiency for a depletable water stock (Krause *et al.*, 2003). That rule characterizes dynamic economic efficiency and is:

$$\mathrm{PVMNB}_{11} = \ldots \mathrm{PVMNB}_{n1} = \mathrm{PVMNB}_{12} = \ldots \mathrm{PVMNB}_{n2} = \mathrm{PVMNB}_{1m} = \ldots \mathrm{PVMNB}_{nm} \quad (2)$$

where the first subscript in each term refers to the use of water (e.g. agriculture, M&I, recreation) and the second refers to the time period in which it is used (e.g. 1,2,3). The equation says that the present value of (discounted) marginal net benefits should be equal for all competing uses and in all time periods. Time itself has a special role in applying this rule. Since each acre-foot[1] of water used in period 1 can take an acre-foot away from a use in different period, the present value of gains should be compared with the present value of losses from future uses displaced. If demand patterns over time change little, then any positive discount rate will produce a declining water use path over time for which the dynamic equi-marginal rule above holds true (Custodio *et al.*, 1998; Timmins, 2003).

2.2. Equity

Equity is an important water resource management objective (Tol, 2003). The equity objective is concerned with fairness of allocation across economic and political groups. It often conflicts with economic efficiency. In the case of household water, an equitable allocation suggests that all households, regardless of their ability to pay, maintain a human right to safe and healthy water (e.g. United Nations, 2002). Baker (1998) describes several non-economic efficiency objectives that could be used to measure social values and hence improve the power of objective science to manage water systems for improved social benefit.

In November 2002, the United Nations took the unprecedented step of formally stating that access to safe water is a human right (United Nations, 2003). The 145 countries that ratified the document agreed to ensure that all their citizens have access to safe and secure drinking water and sanitation facilities.

[1] An acre-foot is a volume of water consisting of a surface acre one foot deep, or about 1234 cubic meters.

Despite these good intentions, progress since 1990 has been slow in providing safe drinking water for the estimated 1.1 billion people who lack access to it (Moore *et al.*, 2003). Sanitation progress has been worse; about 2.4 billion people still lack access to a safe latrine (Pruss *et al.*, 2002). Unsafe water and poor sanitation have been found to be major sources of diseases, including malaria, cholera, dysentery, schistosomiasis, infectious hepatitis and diarrhea (Gadgil, 1998). Inadequate water and poor sanitation are major contributors to poverty. Policies that meet the equity objective may require government subsidies or free service, or at least adjustments to pricing structure to income or family size. As another example, the equity objective may suggest providing enough water for irrigated agriculture at a sufficiently low price so that farmers make enough income to keep their farms (Robinson, 2002; Smith, 2004). Under the equity objective, the poor, women and other vulnerable groups are important target groups for achieving fairness in water resources development and management (Cohon & Marks, 1975; Troesken, 2002).

2.3. Sustainability

The principle of sustainability received widespread attention around the world after the publication of the 1987 Brundland Report (Brundtland, 1987) by the United Nation's World Commission on Environment and Development. It defined sustainable development as development that meets the needs of the present without compromising the ability of future generations to meet their own needs. Water resource economists and others have attempted to establish several standards for implementing the definition of sustainability consistent with the one offered by the Brudtland Report (Hediger, 2003). Examples of such standards have included non-declining consumption per capita, sustaining production opportunities, sustaining use of water resources, a non-declining natural stock of capital and sustained ecosystem stability and resilience. One method for revising the national income accounts to measure the potential of sustainable development is to estimate a green-adjusted NDP. It modifies the conventional national income accounts to keep track of the long term impact of renewable and non-renewable water resource depletion as well as accounting for environmental damages from water pollution. Sustainability does not mean minimizing change, and in fact, its implementation may require dramatic changes in current water use patterns and in water institutions that influence those patterns. Much policy research remains to be done on ways successfully to implement the sustainability objective.

3. Ex post analysis: mechanism evaluation

3.1. Water laws

What the hydrologic cycle supplies in quantity, location and time rarely matches people's demands. How water is developed and used for human benefit depends critically on the status of the law regarding who has legal rights to own, develop or use water. Application of the principle of economic efficiency has considerable potential to judge the effectiveness of existing water laws based on whether or not the benefits of the law exceed its costs. Water law, properly designed and enforced, can compensate for the mismatch between water's natural supply and its human demand. Good water law must be flexible, evolving in response to changes in human values, technologies, political systems and settlement patterns

(Garrido, 2000; Wollmuth & Eheart, 2000). Allan (2003) describes ongoing efforts to develop legal structures that combine the best provision from water laws around the world.

Under riparian water law, the right to use water is a relative right and not a right to a fixed absolute quantity (Burke *et al.*, 2004). It increases in wet periods and decreases as existing riparians find new uses for water. Riparian rights to use a specific quantity of water are insecure in situations in which there is too little water to accommodate all the desired uses. Where the riparian doctrine is applied to water use in dry places, the outcome can produce inadequate and unreliable supplies for everybody (Wollmuth & Eheart, 2000). Prior appropriation law assigns water rights to the first person who takes it from the stream and puts it to beneficial use, which is typically interpreted as any use that avoids flagrant waste. While riparian law views all water right holders as having essentially equal legal use rights, prior appropriation creates a system of priorities in which the first user has superior rights over later-comers (Cosgrove & Johnson, 2004). Historically, the first person to divert water for irrigation, mining, or other beneficial use had a senior water right. A senior right is an absolute right to continue all historical beneficial use. Later users have junior rights, meaning they could claim use rights over only that part of the watercourse not already used by the senior user. Appropriative rights require continued beneficial use: Once beneficial use ceases, the right may be lost (Fleming & Hall, 2000). Appropriation doctrine is not without its detractors, particularly where the need to demonstrate continued use discourages investments in water conservation measures. Economic analysis has the potential to perform important services in the evaluation of existing water laws.

3.2. Regulations

Government has a potential role in influencing water allocations and affecting economic efficiency by regulating various dimensions of water use (Schroder *et al.*, 2004). Where market failures block economically efficient water use patterns, regulations can be an important way to implement certain water use policies. Regulations can be set on water use levels, quality or pollution levels, timing of use, place of use or water transfers. Supported by an underlying legal framework, regulations require, permit or restrict particular activities or prescribe specific results in connection with water use. For an existing regulation to be economically efficient, the economic benefits of the regulation needs to outweigh its costs. Involvement in regulation redesign would be targeted and concentrated on the major areas of the problem and where the highest economic efficiency (additional net benefits) could be produced (Wollmuth & Eheart, 2000; Bakker, 2001).

3.3. Supply adjustment

3.3.1. Imports. Globally, some of the fastest growing places are in arid regions, where there is little natural water available (Abahussain *et al.*, 2002). An interbasin transfer involves removing water from its river basin of origin and exporting it to a destination basin, typically to places where water is scarcer and/or political power is greater (Sneddon, 2003). For example, one interbasin transfer proposal in the USA that has been around since the 1960s is taking water out of the Mississippi to recharge the Ogalalla aquifer to serve high plains irrigated agriculture. More recently, there have been proposals to load water in tankers to be shipped to dry regions in Asia or in the Middle East. For example, in 2002 a company filed an application with the California Department of Water Resources to remove 30,000 acre-feet of water each winter from two Northern California rivers, pump the water into battleship-size bags and tow them to San Diego (Sax, 2002). While such a shipping project may be technically feasible, it is unlikely to be economically efficient. Interestingly, it would relieve only about 4% of California's current 800,000 acre-foot overdraft from the Colorado River. In any event, history has shown that economic analysis of most interbasin transfer proposals found that these transfers fell short of the economic efficiency standard long before they were blocked by legal, political or environmental constraints.

3.3.2. Storage. The natural variability in precipitation with a single year and between years produces a highly variable natural supply of water flowing in streams and rivers. In wet periods, high precipitation has the effect of increasing streamflows when farms, factories and homes least need the water. In droughts, low precipitation reduces streamflows at just the time when water users need more (Agarwal, 2002). Without some mechanism to store unused water for later use in dry periods, mismatches between supply and demand create water shortages and floods, sometimes producing disastrous effects. Building storage tanks, creating reservoirs and recharging underground aquifers can produce benefits that exceed costs by making available a steady stream of water to match human needs during times when precipitation and streamflow produce too much or too little (Merrett, 2002b).

3.3.3. Treatment. The economics of water treatment asks the question of whether it is economically desirable to remove undesirable natural materials and/or remove artificial pollutants (Segerson & Walker, 2002). One example of treatment is desalination of sea water or mineralized water to produce freshwater. Desalination consumes large amounts of energy and presents a waste disposal problem. Therefore it is economically feasible only in places where desalination is cheaper than freshwater, such as dry coastal areas and dry inland regions well endowed with saline groundwater.

Building and operating treatment plants raises the cost of delivered water. Costs increase according to the kind and range of pollutants in the water as well as the degree of purification required. Because the quality of water required by different kinds of users varies, one question, known as the dual supply debate, centers around whether or not all customers of a utility should receive water of an equally high standard. The debate focuses on whether users with more limited quality needs, such as agriculture, should receive water treated to lower standards, while customers such as households should receive water treated to higher standards (Merrett, 2002b). Cost benefit analysis has considerable potential to contribute to this debate. If the cost added by building and operating a dual supply system is smaller than the incremental net benefits of limiting treatment of some customers to a lower level, dual supply is economically efficient. The incremental net benefit produced by adding a dual system is the cost savings of treating water to a lower standard minus the reduction in benefits accruing to users of the lower standard treated water. If, for example, agriculture suffers no loss from water treated to a lower standard, its reduction in benefits from reduced treatment standards are zero.

3.3.4. Distribution systems. Water distribution systems are built to deliver water from water sources to users. A distribution network can consist of pipes, pipe junctions, pumps, valves and storage tanks or reservoirs. By pooling risks, integrated water supply networks reduce the overall need for safety margin capacity in which normal supply is sized intentionally larger than normal demand (Madulu, 2003). Where there is a shortage of demand in one region and a shortage of supply in another, inter-regional transfers can be set up. These often require investments in reservoirs, pipes, pumps and the like. In urban areas, water for households is commonly delivered by main pipes, with a separate connection to each house or to each block of apartments. The design, maintenance and repair of water distribution systems is both important and difficult (Formiga *et al.*, 2003). For new systems, sizing is especially important, as it requires planning for possible future expansion. The designer must determine current and forecast demands as well as water supplies available.

Water distribution systems must deal with the problem of leaks. Investments in leakage control produce the greatest net benefits where water is scarce and/or where the cost of new capacity is high (Buchberger & Nadimpalli, 2004). For a given demand requirement, a lower leakage rate permits considerable savings by building lower capacity systems. In situations where demand is at or near capacity, loss allows for fewer additions to capacity to meet growing demands that would otherwise occur. As the price or environmental cost of water supply expansion increases, it becomes economically feasible to invest more heavily in leakage control (Gullick *et al.*, 2005).

3.3.5. Reuse and recycling. Some water consumers, typically in the industrial sector, consume only a portion of the water supplied to them. They can re-use that portion for themselves repeatedly, though water treatment may be required to maintain the process. Two sources of environmental benefit produced by recycling are (1) use of recycled water requires removing less water from its natural source and (2) reduced pollution in wastewater (Al-Jayyousi, 2003).

Most of the benefits of water recycling accrue to people other than the direct water buyer, so there is typically the problem of inadequate financial incentive facing individuals to encourage recycling. That is, the individual typically sees that it is cheaper to meet his/her water needs by purchasing utility-supplied unrecycled fresh water than to invest in typically expensive recycling processes. Therefore, economic analysis has considerable potential to contribute to designing economically efficient recycling programs, including the issue of how recycled water should be priced compared to its unrecycled substitute. Casanova *et al.* (2001) also explain that unrecycled water typically has a higher economic value than recycled water because of fewer health hazards. Almato *et al.* (1999) describe methods for identifying when water recycling is economically feasible for the case of industrial uses of water in India. Much more research is still needed on establishing a consistent framework for the analysis of conditions under which recycling is economically efficient (California State Water Resources Control Board, 1997). Water recycling becomes economically efficient for any of the following reasons: new water capacity becomes more expensive, the price of recycling falls, recycling economic efficiency rises, and environmental costs of new freshwater sources are higher. To more reliably identify these thresholds, further work is needed in identification and measurement of non-market benefits and costs, especially environmental damage reduced by avoiding new tapped freshwater sources (Exall *et al.*, 2004).

3.4. Demand management

Demand management refers to methods that avoid water shortages by limiting demand. It focuses on greater use of existing supplies, reducing demand or altering the timing of demands – to avoid the need for new supplies. Al-Saffar (1998) presents an analysis using the example of Kuwait. Demand management aims to squeeze more beneficial use out of existing supplies through better management, leakage reduction, improved revenue collection, regulations enforcement, recycling, technological change, metering, pricing and markets. All are intended to stretch existing supplies and produce more user benefits with the hope of making existing water resources go farther.

In many dry places, urban populations continue to grow and these people need water. Where this occurs, hydrologic, environmental or political constraints can block development of additional water sources or escalate their costs. For these reasons, there is growing interest in transferring existing water supplies among users in the search for economically efficient ways of meeting these growing demands. A recent economic analysis of an interbasin transfer is presented by Basson & Van Rooyen, 1998.

One way to transfer existing water supplies to meet growing urban demands is through legislative or administrative fiat. For example, growing cities could simply condemn water rights of farmers and take it for their needs, stating that the public welfare is served. For example, recently the Texas State Senate passed a bill that establishes requirements before a city can declare eminent domain of a private landowner's water rights (Texas State Senate, 2003). The bill recognizes that potential damages to farmers' water rights are posed by condemnation. The bill requires a municipality to prove condemnation is needed by showing (1) that the city really needs the water and the (2) cheaper water supply methods are not possible, and that (3) voluntary market transfers are not possible.

One problem with administrative (non-market) water right transfers is that they can impair existing water right holders and/or water users as well as discourage the search for the cheapest source, including demand-side reductions. One cheaper method of finding new water supplies is the use of water markets to encourage transfers to meet new demands, as long as third party effects resulting from the transfer are protected. A water rights market can function like other markets. Willing buyers and sellers can conclude private agreements to transfer given amounts of water at agreed prices. There is considerable interest in expanding the role of water markets. In many western US states, where much water is locked into agriculture, it has been difficult to transfer water. But experiments are under way. For example, the 1992 Central Valley Improvement Act allows farmers who receive water from California's Central Valley Project to sell or rent some of their contracted water for beneficial uses either inside or outside the project area. Carey and Zilberman (2002) found that where property rights are poorly defined, markets are sluggish to operate unless there are very large differences in the economic value of water between buyers and sellers. Ward and King (1998) describe several methods for implementing voluntary market water transfers.

Several existing conditions are required to harness fully the power of the market institution to promote economic efficiency in water use. These conditions may be hard for some communities to meet for political, economic or cultural reasons. The conditions are as follows. There must be a property right for the use of a certain amount of water that can be defined is secure and is transferable. Brennan & Scoccimarro (1999) emphasized the importance of secure property rights for effective water markets. Burness & Brill (2001) show losses produced by common property institutions for the case of New Mexico. In many communities, the ownership of water resources is held in trust by the state, but the right of use is granted in several forms. These include perpetual concessions, permits, licenses, contracting rights and outright ownership. The use right must be measurable in well-defined terms and be easily measured in the field using practical methods that requires minimum specialized knowledge.

For water markets to contribute to meeting growing demands where supplies are fixed or unstable, a number of policy questions must be resolved. What is a good way to reduce the incentive for new water use that would not otherwise take place in the face of short-term water transfers such as banking (Galaz, 2004)? If cities pay water rights holders to reduce their water use, some owners may start using as much water as possible to establish a higher baseline level of use (Waswa *et al.*, 2002). There may be problems from failing to account for the relationship between surface and groundwater. It is common for two-party transfers between agriculture and other water users to affect third parties, such as local communities and environmental interests. Some institutional mechanism is needed to assure that all interests are protected (Hargreaves, 2003). Market-based water transfers are likely to work better in places that have extensive conveyance systems and storage facilities and with well-coordinated operations. For other locations experimentation with better organization and/or development of conveyance and storage facilities may be required to make short-term water trading work.

3.5. Population growth

Global population pressures continue to stress existing water institutions. These stresses have produced many institutional responses, including a shift away from developing new supplies to a growing emphasis on incorporating ecological values into water policy and an increased emphasis on institutional flexibility for economically efficient and fair allocation. Loaiciga & Renehan (1997) identified the role of water pricing in dealing with shortages caused by population growth combined with unprecedented drought. They analyzed average water revenue, water use and the average cost of water supply in the City of Santa Barbara, California, from 1986 to 1996, a period that included one of the most devastating droughts in California the 20th century, as well as a period of high population growth. That drought provided an opportunity to assess the sensitivity of municipal water use to pricing, conservation and other water management measures under extreme drought conditions. The analysis showed that the average cost of water rose more than three-fold in real terms from 1986 to 1996, while the gap between the average cost of supply and the average revenue per unit of water rose in real terms from US$0.14 in 1986 to US$0.75 in 1996. Water use dropped 46% at the height of the drought relative to pre-drought water use. The data derived from the 1987–1992 California drought provided an opportunity to conduct an experiment in which declining water use varied with declining water supply and increased water price. The experience incurred in coping with drought during that period points to the possibilities available for future water management in dry places around the world.

Beaumont (2002), in an analysis of the Middle East, emphasized the importance in reallocation of existing supplies as a way to cope with population growth in dry places. Detailed analyses of the available water resources showed that most of the countries of the Middle East will be able to meet the water needs of their citizens up to 2025. However, to achieve this, the reallocation of at least some water from irrigated agriculture to other uses will be required. Three countries - Jordan, Oman and Tunisia - will experience major problems of water supply, but all three can manage these problems if they develop institutions that smoothly transfer water from agriculture. Casanova *et al.* (2001) analyzed the potential for coping with population growth through conservation and reuse and found that both methods have considerable potential for reducing water scarcity as long as the potentials for disease transmission risk is managed properly. Shin (1999) examined innovative institutions in northern China that could be used to cope with shortages caused by population growth and focused on water conservation through demand management, pollution control and importation of water from other river basins. As a general principle, in poor countries where per capita water use is already very low, supply augmentation is expected to be a cheaper measure than demand reductions for dealing with shortages caused by growing populations.

Water transfers supported by a public administrative structure could be a policy mechanism for reallocating water resources to support growing or shifting populations. Keenan *et al.* (1999) compared preferences by residents of the Grand Valley of western Colorado and the San Joaquin Valley of California for coping with growing scarcities. They found that residents of a water-exporting area are more likely to oppose water transfers than were residents of a water-importing area. Nevertheless, residents of these two very different areas of the western USA west had strong reservations about free markers as a mechanism for allocating water. It is fair to say that population growth will continue to cause stress to water supplies and water institutions around the world. The evidence suggests that market water transfers are a cheaper method for meeting future demands than new water supply development, as long as the public is fully informed and/or compensated for costs incurred by the transfers (Bjornlund, 2004; Nieuwoudt & Armitage, 2004).

3.6. Climate change

Several recent works have examined the economics of water management as it relates to climate change (e.g. Kundzewicz, 2002). One recent analysis addressed how global climate change could affect the discounting procedures used to evaluate water resources programs and projects (Lind, 1997). The author used the example of the primary US document governing water resource planning and evaluation today (US Water Resources Council, 1983). Mendelsohn (2000) examines the implications of climate change for water management. The author concludes that private firms and individuals are likely to engage in substantial private adaptation with respect to climate change in such sectors as farming, energy, timber and recreation. Because the shared benefits of joint adaptation to climate change are a public good, individuals will underprovide joint adaptation in such areas as water control, sea walls and ecological management. Middelkoop *et al.* (2001) examine innovative institutions for coping with climate change for the case of the Rhine basin in western Europe. They find that climate change can affect numerous economic sectors. Balancing the required actions against economic cost and existing uncertainties in climate change scenarios, a policy of minimum regret combined with flexibility in water management planning and design is recommended. The authors emphasize anticipatory adaptive measures in response to climate change.

4. Ex ante analysis: institutional design

4.1. Marginal cost pricing

Many cultures treat water as a free resource (Kanakoudis, 2002; Yang *et al.*, 2003). While this institution produces desirable equity properties, it can impose considerable burdens on financing uses that exceed basic human needs (Bakker, 2002). So economic analysis faces major challenges in the search for institutions that encourage more careful (higher-valued) use of high-cost water. Responding to the problem of weak incentives provided by underpriced water, some have called for the promotion of a water ethic together with incentives and sanctions for responsible use of water (e.g. Lundqvist, 1998). One way to promote responsible (economically efficient) water use is to establish institutions that confront all water users with the real cost of their actions. When that occurs, each water user implements only those actions for which his/her own benefits exceed his/her costs. However when water users faces the real cost of their action (benefits displaced from other uses), they implement water use decisions for which society's total benefits exceed its total costs. Creedy *et al.* (1998) show why group-metered or non-metered water reduces incentives to conserve water compared to individual metering. Johansson *et al.* (2002) review water pricing methods for irrigation. Duke *et al.* (2002) provide one of the few analyses of the poor performance on equity grounds of marginal cost pricing compared to simple non-price rationing. Economically efficient water supply requires clear price signals that provide incentives for economically efficient use of water by individual consumers, resulting in total benefits of the water exceeding costs by the greatest amount possible. One method for promoting that economic efficiency is marginal cost pricing in which each water user pays a price that reflects the incremental cost of their use on the system (Chambouleyron, 2004). Marginal cost pricing is an important concept for understanding the economically efficient management of water supply systems. Setting the price of water equal to marginal cost means that each customer pays a price equal to the incremental costs they impose on the system for providing that service. This price provides valuable information for water buyers and provides a basis for making informed decisions regarding water use. Several widely practiced ways of implementing marginal cost pricing are discussed below.

Connection charges are imposed for installing distribution systems for new residential or industrial developments. They can take the form of lot charges, frontage fees or development charges. Recovering these costs through increased water prices signals important messages about the costs that new developments impose on water distribution systems. Pricing this new water use at its full marginal cost results in economically efficient growth in system size, both in terms of limiting urban sprawl and limiting expensive, self-supplied connections that occur in rural areas (Garcia & Reynaud, 2004).

Externality charges are a form of marginal cost pricing in which each water user can be charged a price that reflects the social costs of their water use (Chambouleyron, 2003). For example, take the case of waste treatment systems sized and designed to treat organic wastes. Some individual users, often industries, discharge wastes that are high in volumes and/or strengths. These users impose added costs on the utility. In regard to waste collection and treatment, emissions of extra strength waste impose higher costs on treatment systems than emissions from typical residential users. Externality charges on industrial waste that exceeds existing purification capacity, a form of marginal cost pricing, could be levied where relevant. This method is often used by large cities that treat large volumes of industrial wastewater.

Geography can influence the marginal cost of delivering water. Customers located at higher elevations, for example, impose significant added pumping costs compared to those on level ground. Also, service units at the edges of systems produce higher costs. In principle, if rates are based on marginal costs, each of these factors will influence water rates and will prompt greater economic efficiency in water use (Hajispyrou *et al.*, 2002).

Water markets can be an economically efficient institution for implementing marginal cost pricing. That is, the market price paid by the buyer to a potential seller signals the marginal cost of continuing to use water in its existing use (Rosegrant & Binswanger, 1994). The price charged by the seller reflects the marginal cost of existing uses that have been displaced. In either case, the market price incentive encourages the resource to move to its highest valued use, producing economic efficiency as long as all incremental costs are incorporated in the market price. Bauer (1998) describes the challenges that have faced Chile, which in the early 1980s adopted water markets to improve water allocation economic efficiency. Bjornlund & McKay (2002) describe similar challenges facing many developing countries, especially when related to prices that signal the marginal cost of water use while protecting human rights for the most vulnerable. The implementation of water markets often requires investing a considerable cost of administrative and institutional support. These costs include the high cost of measuring and defining property rights with variable and random streamflows as well as the cost of enforcing rules on a set of owners, each of whom may have a property right of possibly varying security of tenure. For example, the high cost of engineers and lawyers required for adjudications has blocked most western states in the USA from completing their stream adjudications. The State of New Mexico, as of the year 2006, has finished only about one-quarter of those adjudications. One of the biggest problems related to development of markets is the high cost of initiating the change produced by the transition from existing non-market water allocation mechanisms to a market environment. A good example is the high cost of discovering historical water use patterns. This information typically is required prior to adjudicating water rights and may be a necessary prerequisite for establishing a market system.

Peak load pricing is the practice of charging higher prices at times of peak demand (Bakker *et al.*, 2003). Its rationale is that much of the capital expenditure on water utilities stems from meeting peak demands, particularly summer residential water demands in hot areas. Peak load pricing can promote economic efficiency by informing customers of the added cost of their peak period use. That price information can have a significant effect in reducing demands in peak periods and, therefore, lowering capacity expansion costs over time (Bakker *et al.*, 2003). Peak load pricing can also be an economically efficient way to promote water conservation, since it provides incentives for reduced water demands during the period in which water supplies are most likely to be constrained. An economically efficient decision to expand capacity requires a comparison between expected benefits and costs of the new facility. Marginal cost pricing can significantly contribute to water conservation programs by informing managers of a conservation program's costs and benefits. It may be economically efficient to delay the need for new facilities through a price signal to consumers in peak use periods. The benefits produced by delayed construction can be compared with cost of consumer surplus lost from reduced water use instituted by the surcharge. When done economically efficiently, a conservation surcharge sends the correct signals to consumers regarding the cost consequences of expanding existing water use. To meet growing peak demands, many systems face the prospect of a finite water supply or limited treatment capacity, both of which require significant capital investment. High costs of capacity expansion programs can be magnified by the need to develop new storage, production or supply (Rosegrant & Cai, 2002).

4.2. Politically workable marginal cost pricing

Even the strongest supporters of marginal cost pricing realize that it can be politically dangerous. Careless implementation of marginal cost pricing risks pricing a basic human need so expensive that the poor cannot afford their water requirements without shouldering a politically unacceptable burden. In fact, before 1990 only one major American city - Tucson, Arizona - ever adopted marginal cost rates for water. This occurred after the two-year drought of 1976–77. One year after the adoption of those rates, the voters held a recall election over the water rates and voted the entire city council out of office. Similarly, after the six-year California drought of 1986–91, Mayor Bradley of Los Angeles appointed a Blue Ribbon Committee for Water Rates. The committee was given Tucson as the example of the political danger of using marginal cost rates for water. The committee responded by designing politically workable marginal cost water rates that have stayed mostly intact since their inception. Politically workable marginal cost pricing is based on this idea: A low price is charged for basic needs such as showers, toilets, cooking and drinking. But for luxury uses like car-washing, driveway watering, ignoring leaky pipes and watering landscapes, water is priced at marginal cost (Hall, 2000).

4.3. Multi-tiered pricing

A special kind of marginal cost pricing, multi-tiered pricing, combines elements of economic efficiency, equity and sustainability. Pricing water at a low or zero price, which is attractive on equity grounds, makes it difficult for the utility to pay for its costs of operation. Still, many debates center around the hypothesis that total cost recovery adds more to the costs of hardship than it promotes in the benefits of sustainable development. In many poor areas of the world where privatization of water has been implemented, millions of people have been cut off because they cannot afford to pay water bills. In some cases, the bills amounted to more than 30% of family incomes (Goldblatt, 1999), although these percentages are widely debated (e.g. McPhail, 1993). One way to deal with the conflict between equity and economic efficiency–sustainability is to set up a two-tiered pricing system in which the price for all water use in excess of the required minimum is raised to a level higher than average cost. As described by Agthe & Billings (1997), the price should be high enough to make up for the financial losses from pricing basic needs below average cost. This price structure ensures the financial sustainability of the utility. A two-tiered water pricing system presents three advantages:

- *It Promotes Equity By Supporting Human Rights*: nobody's health suffers from bad water or water they cannot afford.
- *It Encourages Economic Efficiency*: by charging a price approximately equal to the marginal cost for all use levels exceeding basic needs, price signals the real scarcity of expanding system capacity.
- *It Is Financial Sustainable*: by producing revenues adequate to cover costs, the utility and its water supply can last for future years.

4.4. Valuing water in alternative uses

4.4.1. Economic value of water. Economically efficient decisions supporting water resource development, allocation, conservation, recycling, purification and protection may require measuring the value of water in alternative uses. When the market system works, markets allocate water and supporting resources to activities yielding the greatest total economic returns. However, owing to the difficulty of capturing and holding water and because its supply is often subject to unexpected changes, it is typically expensive or impossible to define, establish and enforce the property rights that a water market system requires (Duan *et al.*, 2001).

Taxpayer resources supporting water development and allocation and the water itself typically have many uses; hence, there is a compelling need for information on the economic value of water proposals and plans so that benefits can be compared to costs. One important question along these lines is which taxpayers' welfare counts? The answer depends on what accounting stance is taken. Many accounting stances are possible, including local, regional, national or global, as described by Howe (1987).

The economic value of water comes from the many uses to which water can be put in satisfying human needs. The economic value of water is defined as the amount that a rational user of a publicly or privately supplied water resource is willing to pay. Defining value in this way assumes economic efficiency is the objective. Other values can be defined for other objectives. It also assumes that more water is better, which is not always the case. For example, Baecher *et al.* (1980) describe how the risks of avoiding dam failure can be incorporated into benefit-cost analysis. Bose *et al.* (2001) describe methods for valuing water for the case of India using non-economic efficiency objectives.

Willingness to pay for water reflects the water user's willingness to forego other consumption and is measured by a demand schedule relating the quantity of water used at each of a series of different prices. For any potential quantity that could be supplied, demand is limited. So the economic value of an *added* unit of water supplied decreases as greater quantities are offered to water users. For example, most people will use water only for irrigating their lawns or for low-valued crops if the price of water is suitably cheap. At a high price of water, neither of these uses produces a high enough economic value to make it affordable. Water policy decisions typically focus on proposed marginal changes to existing supplies or qualities, so economic values of the marginal unit provide important information to inform those debates. Some analyses of total quantities have been conducted, for example Costanza (1999) who estimated the total existing economic value of the world's oceans at US$21 trillion per year.

Quantity supplied is only one dimension of water's use. Time utility of water use can be improved by building dams and developing groundwater reserves, while location utility can be improved by building water transport systems such as aqueducts to move water to places far from the natural watercourse. Moreover, location utility itself is measured in three dimensions, since ground water is increasingly expensive to put to beneficial use with increasing depth and increased energy prices. It is cheaper with increased technical pumping efficiency. Finally, water may be of varying qualities depending upon the soils through which it moves or depending on how people affect the water in supplying or using it (Young & Haveman, 1985).

4.4.2. Measuring water's economic value. Market prices for water offer an opportunity to observe its economic value directly. Nevertheless, where market transactions are recorded, analysts should use the price with care. There are several types of market transactions in water. One example is the short-run water rental market, such as the one that was set up for coping with the 1990 California Drought (California Department of Water Resources, 1992). The water right owner maintains the title to the annual water use but sells, rents or leases their unused water for some specified period of time. For example, a farmer may rent, for one irrigation season, 500 acre-feet of water to another farmer, or deposit the water in a state or privately run emergency drought bank or rent it to an environmental group for endangered species critical habitat. Transactions in permanent water rights occur in some places (e.g. Bjornlund, 2003, for Australia; Bauer, 2004, for Chile; Brookshire *et al.*, 2004 for the western United States). Still these transactions must be interpreted carefully, since land to which the right pertains is often involved in the transaction, so the market value of the water right may include land and water. The observed transaction price of transfers between similar water right users is the correct measure of the long-term private value of the water used for that purpose. However, if a water right has junior standing, such as in Colorado (USA), and does not always receive the full supply in dry years, the observed price will be less than the value of a senior right with a guaranteed supply. Second, the price of a water right is for a right to a perpetual series of annual flows which vary considerably from one year to the next. It does not necessarily depend on a given volume of water in the river in set time period.

An administered price is a price set by a regulation or institution and not by the forces of supply and demand. Good examples are irrigators who are charged a fixed price per unit of use by an irrigation district or homeowners who buy water from a public or private water utility at a set price (Berbel & Gomez-Limon, 2000). If the buyer is free to adjust their use to meet their needs at the specified price then statistical analysis of data pertaining to the relationship between water consumption and price (a demand schedule) can be used to measure the economic value of water to the final user. Still, even if water is subsidized, the subsidized price is a good estimate of the short-run marginal value if a user may purchase all quantities desired at that price (Young & Haveman, 1985).

When the water resource in question is an input and is used to process a commercial product, the producers' change in net income is a good measure of the water's economic value. In this case, the demand for water is derived from its use in producing a final product. In this case the water user is willing to pay for the water up to an amount equal to the change in net income produced by the water. The change in net income can be used to estimate the economic value of water resources that contribute to the production of commercially marketed goods. A good example is the case of increased water quantities or water quality improvements that increase the productivity of crop-irrigated lands. Crop-water production functions (e.g. Moore & Negri, 1992) are the basic building block for valuing water in agriculture. Amir and Fisher (2000) describe an elegant optimization model for allocating and valuing water used in irrigation, using the case of an integrated farming system in Israel. Two other examples of the change in net income method include programs that reduce the costs of treating municipal drinking water and increase the productivity of industries that require clean water. The economic benefits of a policy that increases water quality can be measured by the increased net farm-level income from increased agricultural productivity, the reduction in costs of supplying drinking water and the increase in net income of a computer chip maker (e.g. Acharya, 2000; Acharya & Barbier, 2002).

When a water program enables water users to avoid certain future costs, these costs avoided are a real benefit for which there is a willingness to pay. Three applications of the avoided cost approach are (1) damage costs avoided, (2) replacement cost avoided and (3) substitute costs avoided (e.g. Abrahams *et al.*, 2000). They are based, respectively, on the costs of avoiding damage suffered by lost services, cost of replacing water services and the cost of supplying substitute services. These methods bypass the need to measure directly beneficiaries' willingness to pay. Instead, they recognize that the costs of avoiding damage, or replacing water systems or their services can sometimes be at least as large as the willingness to pay for these services. The validity of the method rests with the assumption that, if people will voluntarily incur costs to avoid damages from lost water services, then those services must be worth at least what people are paying to protect, replace or substitute for them. Here are a few applications: (1) valuing water quality improvements by cost of controlling (avoiding) pollutants into the water; (2) valuing a forest's erosion protection services by the avoided cost of cleaning up downstream muddy water; (3) valuing a wetland's water treatment services by the avoided cost of artificially treating water; and (4) valuing fish habitat by the avoided cost of fish hatcheries. However, if the avoided costs would not have been incurred voluntarily, then those costs inflate the economic value of the program, so their use will justify economically a weak program (Young & Haveman, 1985).

Hedonic pricing refers to methods used to attach value to water-related environmental assets that directly affect market prices. It is most commonly applied to variations in housing and real estate prices that reflect the value of local environmental attributes (Luttik, 2000; Ward, 2005). Hedonic pricing can be used to estimate economic benefits produced by: (1) water quantity or quality improvements and (2) water-related environmental amenities, including aesthetic values or access to outdoor recreational areas. For example, the price of a home surrounded by polluted water may sell at a discount compared to the price of an equivalent home surrounded by unpolluted water. Therefore, one can value the individual characteristics of a home, including size, number of rooms, number of garages and air quality by seeing how the price varies with changes in its characteristics.

Travel cost models (TCM) can be used to estimate values produced by water-related environmental resources as outdoor recreation sites. Four kinds of policies can be valued using TCMs: (1) changes in the cost of accessing a recreational site, (2) closure of an existing recreational site, (3) opening a new recreational site and (4) increases or decreases in water quality at a recreational site. The TCM is based on the principle that travel cost is an expense people incur to visit a site and greater distances from a site effectively raise the price of its access. So observing the impact of increased distances on visit rates effectively traces out a demand function for the site. Visitors' benefits produced by the environmental resources at a site can be estimated by observing the reduction in visit rates at various increased travel costs. Ward & Beal (2000) describe a wide range of uses of the TCM to value environmental assets.

The contingent valuation method (CVM) measures the benefits of environmental improvements by eliciting people's willingness to pay (WTP) or willingness to accept payment (WTA) for changes in quantities of environmental services. The usual method of eliciting those benefits is to survey people. Many kinds of environmental assets, such as water quality at recreation sites, wildlife habitat, water pollution control, streamflows for recreation (e.g. Berrens *et al.*, 1996), groundwater protection (e.g. Bergstrom *et al.*, 1996) and outdoor recreation have been valued using CVM surveys. CVM surveys also have used to value more complex environmental programs, such as hazardous waste reduction, endangered species' habitat protection and human lives saved (e.g. European Union, 2004). The use of CVM as a method for estimating both costs and benefits continues to grow. For example, for cases involving natural resource damage assessments, US federal courts have elevated the results of citizens' environmental valuations to the level of rebuttable presumption (Murray, 2005). Presumptions are valuable because they are used to relieve a party from the cost and burden of proving the truth of the presumed fact. However, once a party relies on the truth of the presumption, an opposing party may be allowed to present evidence to rebut the presumption. When a fact reaches the status of a rebuttable presumption, the person supported by that fact has a valuable property right. A blue ribbon panel of social scientists convened by the National Oceanic and Atmospheric Administration in 1993 (Arrow *et al.*, 1993). They further supported and defended the use of CVM for inclusion in natural resource damage assessment cases by finding that it could be the basis for estimating damages (benefits lost).

CVM supporters observe that contingent valuation is quite flexible because it can be used to estimate the economic value of virtually any environmental improvement. However, it is best suited to estimating values for environmental services easily identified and recognized by respondents. While CVM requires well-trained survey analysts to produce defensible estimates, the nature, results, and interpretation of CVM studies are easy to understand, analyze and describe. Monetary values can be presented in terms of a mean value per capita or per household, which can be aggregated to total values for the affected population. Anand & Perman (1999) use the CVM to value increased reliability of water supply for Madras, India. CVM has seen widespread use since the 1960s and a considerable amount of work continues to be conducted to improve its use. Despite considerable recent advances in CVM techniques, much controversy remains over whether it really measures people's willingness to pay for environmental improvements. Its critics believe that many people are not accustomed to placing monetary values on environmental services. Therefore, they may not have a realistic basis for stating their value, even if they knew it. Responses to a willingness to pay question in a CVM survey may be biased because the respondent answers a different question to the one the surveyor had intended. Rather than expressing a willingness to pay for the service, the respondent may be expressing his or her feelings about the policy or the valuation exercise itself.

The aim of a benefits transfer exercise is to adapt estimated benefits from an original site to the valuation question of a similar target site (e.g. Barton, 2002). The need for this method is greatest when it is impractical to conduct an original valuation study, yet some measure of benefits is needed. For the case of water-based recreation, the cheapest type of benefit transfer is to transfer unit-day values from the original site to the target site. Unit-day values, such as X dollars per visitor day of coldwater fishing, are used to value the same activity at the target site. A more defensible, but expensive, benefits transfer is a complete benefit function from another study. The advantage of transferring the complete function is that adjustments are made for differences in all relevant predictor variables between the original site(s) and the target site. The larger the number of original sites and the wider the range of characteristics, the greater is the likelihood that the target area will have environmental and human characteristics bracketed by the previous study areas. The benefit transfer method is most reliable when the original site(s) have conditions that bracket the study site in terms of things like quality, location and population attributes. It is also more reliable when the old and new levels of environmental quality are similar for original and target sites (van Bueren & Bennett, 2004).

4.5. Water quality management

Water quality refers to the chemical, physical and biological characteristics of water with respect to its suitability for a particular use; the same water may be of acceptable quality for one purpose or use and unacceptable for another. Water quality objectives describe how much of a pollutant or combination of pollutants a society will tolerate in its water supply. These objectives could indicate the maximum allowable concentration of substances for a particular water use such as irrigation, boating, fishing, swimming or drinking. They could also specify the concentrations of substances permissible for the intended water uses at a specific location on a lake, river, estuary or other water body.

Two important economic approaches for evaluating water quality programs are cost-benefit analysis and cost–effectiveness analysis. Cost–benefit analysis can be used to decide whether a project should be undertaken, based on computing whether its benefits exceed its costs. Choe *et al.* (1996) conducted a cost–benefit analysis of water quality improvements for the Philippines. A benefit–cost analysis helps policymakers establish economically efficient programs. Cost effectiveness draws on the power of microeconomic theory to compare two or more alternatives that achieve the same objective when the benefits of achieving that objective cannot be measured reliably. Cost effectiveness can be used to find the cheapest method to achieve a given water quality objective or to find which method produces the greatest output in achieving that objective for a given cost (e.g. number of lives saved).

Several well-known analysts have examined the economics of water quality. Horan & Ribaudo (1999) reviewed the physical characteristics of agricultural non-point pollution and discussed the implications for establishing economically effective pollution control objectives and designing incentive-based pollution control policies. They found that policy objectives must be designed carefully to ensure that positive economic net benefits can be expected from pollution control. Next, they reviewed several classes of incentives and recommended the use of design-based incentives, that is, incentives based on variable input use, management practices and land use, for controlling non-point pollution. Ongley (2001) examined some of the special problems facing developing countries challenged by the difficulties of achieving sustained water quality. In many developing countries water quality is the principal limiting factor to water availability. Qiu & Prato (1998) examined how cost–benefit analysis could be applied to the question of finding the most economically efficient spatial pattern of farming systems for improving water quality. They evaluated the economic value of riparian buffers in reducing agricultural non-point source pollution in a midwest US watershed. Schleich & White (1997) analyzed the cost effectiveness of various measures for reducing nutrients in watersheds. They used linear programming analysis to identify the least cost strategy for reaching politically specified phosphorus and total suspended solids reduction targets for the Fox–Wolf river basin in northeast Wisconsin.

Shmueli (1999) showed how the public goods' nature of water quality complicates international treaties dealing with trans-national rivers. The major issue of pollution control in water quality management is often postponed or neglected in treaties concerning international river basins. Deterioration of trans-boundary waters is difficult to deal with by any single nation when both nations contribute to its pollution because the benefits of a water quality improvement project accrue to all nations jointly but the costs are typically paid by one. Verweij (2000) compared pollution levels in the US Great Lakes to the Rhine River in Western Europe and emphasized the importance of institutions that encourage each polluter to undertake voluntary investments in water quality improvement.

4.6. Optimization models

Water-related decisions are improved when available knowledge about the physical and behavioral aspects of the water resources system are used. Well-known connections between the physical and behavioral systems, the physical constraints on availability and movement of water, and the complexities of institutional and legal systems suggest that basin-scale modeling improves comprehensive assessments of proposed water decisions (Zagona *et al.*, 2001).

Many of the problems of identifying economically efficient water institutions have been simplified with the introduction of high-speed personal computers and sophisticated mathematical programming software. Fast machines and good software have facilitated the development of dynamic mathematical models of the hydrology, biology and economics that can encompass the quantity, time, space and quality dimensions of the problem simultaneously. For example, some modern software enables analysts to write algebraic functions that express irrigation, hydropower, municipal and industrial, recreation and environmental values as mathematical functions over the dimensions of quantity, quality, time and location. Two example include software produced by GAMS Development Corporation (2004) and the Center for Advanced Decision Support for Water and Environmental Systems (2004). With empirical expressions for these functions, various institutions that allocate a fixed supply of reservoir water, snowmelt or groundwater supply can be tested to establish water policies that maximize or otherwise optimize total benefits produced by water, subject to the equity constraints of an acceptable distribution of those benefits. Many of these analyses have been conducted in since the mid 1990s.

Integrated hydrologic–economic models at the basin scale have focused on the economic impact of water transfers. Table 1 illustrates the kind of results that can be expected from a basin-wide optimization model (Booker *et al.*, 2005). It shows results of maximization of total economic benefits of municipal and industrial and agricultural uses for the Rio Grande Basin of three US states: Colorado (CO), New Mexico (NM), and Texas (TX). The model was constrained by several institutions that divide the flows of the Rio Grande among the three states and Mexico. Results show total economic benefits by sector and state under various drought scenarios as well as for three possible levels of in-tream flow protection for endangered species. The scenarios would provide minimum year round streamflows of 0, 50 cubic feet per second

Table 1. Economic Impact of Severe Drought and of Instream Flow Protection for Endangered Species, Rio Grande Basin, USA, 2004 ($US, thousands).

Drought & in-stream flow protection scenarios		Change in economic benefits all – sectors			Change in economic benefits – agriculture			Change in economic benefits – M&I		
Drought conditions % basin inflow	Minimum in-stream flow protection flows (cfs)	**CO**	**NM**	**TX**	**CO**	**NM**	**TX**	**CO**	**NM**	**TX**
Baseline*		0	0	0	0	0	0	–[a]	0	0
60	0	−42,173	−12,027	−4,932	−42,173	−12,021	−4,912	–	−6	−20
	50	−42,173	−11,992	−4,612	−42,173	−11,985	−4,594	–	−7	−19
	100	−42,173	−12,787	−2,682	−42,173	−12,774	−2,672	–	−12	−11
70	0	−29,491	−8,118	−3,432	−29,491	−8,114	−3,418	–	−4	−14
	50	−29,491	−8,118	−3,432	−29,491	−8,114	−3,418	–	−4	−14
	100	−29,491	−8,089	−2,682	−29,491	−8,083	−2,672	–	−6	−11
80	0	−18,290	−4,729	−2,062	−18,290	−4,727	−2,053	–	−2	−8
	50	−18,290	−4,729	−2,062	−18,290	−4,727	−2,053	–	−2	−8
	100	−18,290	−4,729	−2,062	−18,290	−4,727	−2,053	–	−2	−8
90	0	−8,485	−1,980	−890	−8,485	−1,979	−886	–	−1	−4
	50	−8,485	−1,980	−890	−8,485	−1,979	−886	–	−1	−4
	100	−8,485	−1,980	−890	−8,485	−1,979	−886	–	−1	−4

[a] Colorado takes no significant water for M&I use in the Rio Grande Basin.

(cfs), and 100 (cfs) near Albuquerque, New Mexico, to support the habitat needs of the US federally endangered Rio Grande Silvery minnow (*Hybognathus amarus*).

4.7. Integrated management

Integrated demand/supply water management has considerable potential to improve economic efficiency. Water supplies and water demands are managed jointly in the search for least-cost methods to avoid shortages (Lazarova *et al.*, 2001). Practically, this means linking the gradually phased development of new water supply to pricing incentives to reduce shortages caused by growing demands. For example, through conservation and water recycling programs, water utilities can stabilize and sometimes reduce demands. In some cases these demands can be reduced even in the face of increased populations, thus reducing or eliminating the need to implement expensive new supply plans. These new supply plans included reservoir developments, buying farmlands and building pipelines. By tying supply requirements to demands that have been reduced to lower levels, innovative utilities rely on the proven conservation capabilities of customers. This method also avoids incurring the financial and environmental costs of new supply until such development can no longer be avoided.

4.8. Transboundary agreements

One way of reducing the cost of water management as well as increasing the size and scope of its benefits is for two or more nations jointly to develop, finance, manage and use common rivers, where elements of responsibility are assigned to each nation based on comparative advantage. This permits all nations to gain from trade. The Columbia River Treaty between the USA and Canada, signed in 1961, provides an excellent example. The treaty fosters a coordinated plan that manages the Columbia River Basin as a trans-national system for mutual benefit. Storage dams built in Canada meant that downstream users were no longer dependent on seasonal river flows. The dams ensured the necessary amount of water would be in the river to meet hydroelectric demands regardless of season, within the basin and beyond its borders. The USA had a comparative advantage in money and engineering expertise, but suffered from floods. Canada had a comparative advantage in endowments of water but was limited by absolute shortages of taxpayer funds. Both nations secured what they needed most at a lower cost than either nation could have financed on its own. Using the example of North Africa, Askari & Brown (2001) describe how the use of basin-wide optimization models could promote the economically efficient allocation of water among countries that share a common source. Boadu (1998) describe how Lesotho's water treaty with the Republic of South Africa promotes economically efficient water transfers. A major challenge is designing economic incentives that permit all parties to benefit from agreements for sharing trans-boundary waters. When total benefits from an agreement exceed total costs, this is a signal that there is a potential for all parties in a dispute to share in those benefits.

Trans-boundary rivers pose major economic and political challenges in policy design. Designing an economically efficient, fair, and sustainable measure to allocate scarce and random supplies, that meets the needs of all parties is a major challenge, particularly when two or more political units share a water source. One way to allocate these supplies that has been tried with some success is the water sharing agreement. In the USA, for waters extending beyond borders of one single state, interstate compacts have been used. An interstate compact is a negotiated agreement among the states that, once ratified by

Congress, becomes both a federal law and a contract between the signing states. Beginning in 1922 with the signing of the Colorado River Compact, 22 such compacts currently divide the waters of western American rivers (Bennett, 2000).

In the USA, the compacts succeeded partly because the national government is supreme. The potential for an unfavorable allocation through federal action or the threat of costly and time-consuming litigation serve as incentives to negotiate between the affected states. Furthermore, the federal government provides a way to enforce compact obligations; without that potential for enforcement, compacts would have considerably less effective legal force. There are several methods to allocate water. The choice of the allocation method depends on what the negotiators wish to accomplish and how they wish to allocate the risk of shortage. Some collaborative methods for sharing trans-boundary waters are described by Adamkus (2002). Dirksen (2002) describes the challenges faced by the EU in establishing environmentally sound market-oriented water management systems that satisfy all member states.

4.9. Virtual water

Virtual water is based on the idea that reducing the demand for water saves just as much water as developing added supplies and may do so at a lower cost (Allan, 1998, 2003). The principle has important policy implications. Policies based on virtual water would look for ways to reduce the water used by commodities that cannot be produced domestically because of a drought or other water shortage. An example is increasing the imports of foods or other products whose domestic production consumes domestic water. Virtual water still has many details that need to be worked out. Because of the risk of unplanned trade barriers that disrupt food security, relying on food imports for critical food needs is politically sensitive. People can live without many imports, but food shortages can escalate into famine. Still, many dry regions face water crises and some action is needed. So, increasing supplies of virtual water by importing food that would otherwise be irrigated domestically could be an economically efficient measure for dealing with shortages and providing needed water in adequate quantities. The major economic challenge facing proposals for virtual water is to identify conditions in which its implementation is a cheaper method for dealing with shortages than through alternative measures.

4.10. Managing water poverty linkages

Poor water services have doubly adverse effects on the poor, because they promote the spread of disease. Moreover, the health benefits of better hygiene and clean water permit the advantages of having an improved water supply to be more fully realized. Water scarcity and degraded water quality have an impact on health, the food supply and human living conditions. The poor are particularly vulnerable when water is unclean, scarce or unreliable. Sullivan (2002) develops a method to calculate a water poverty index. For example, Asia is home to nearly 900 million of the world's poorest people; gaining access to adequate clean water absorbs a large percentage of an individual's energy and income, especially for women. Difficulties encountered in accessing water frequently worsens the level of poverty (Asian Development Bank, 2001). Water pollution in many third world countries increases the incidence of disease in rural and urban areas. The urban poor spend a large part of their scarce income on water from private vendors.

Where funding from the central government is scarce, more resources can sometimes be found in local affected communities. Efforts could be productively invested in finding out the kind and extent of water services the poor really want. Several studies have found that the poor, both on farms and in cities, are willing to pay for a reliable high quality service (e.g. Merrett, 2002a,b). In fact, the poor often pay more for less and lower quality water, which in many urban third world countries they receive from street vendors.

4.11. Decentralization

Faced by scarce resources, many governments need to choose carefully the responsibilities they take on for water resources. One operating principle is that nothing should be done at a higher level of government that can be done effectively at a lower level. Thus, where local or private capabilities exist and where an appropriate regulatory system can be established, economically efficient central government policies will decentralize responsibilities to local governments and will transfer delivery of water services to the private sector and to community organizations such as water user associations. Governments can accomplish these by privatizing public water service agencies or by encouraging their transformation into financially independent organizations through measures such as the use of management contracts for service delivery. The conditions under which public versus private management is more economically efficient are highly debated. According to Allouche & Finger (2001), the World Bank favors water privatization whenever possible. Bakker (2002) describe the transition from state to market control of water in Spain in the 1990s. Boxer (2001) describe some of the value contradictions in China that would support markets versus government institutions for managing water. Clarke *et al.* (2002) describe the economic benefits of turning over public management to private suppliers in Guinea. Arrangements for ensuring performance accountability and for setting up effective regulatory frameworks can also be economically efficient, equitable and sustainable.

4.12. Common property institutions

The well-known tragedy of the commons is described eloquently by Hardin (1968) and later by Ciriacy & Bishop (1975) and many others given that time gives insight into why common property systems rarely work economically efficiently. However, considerable work in recent years has opened up new lines of research suggesting ways in which the commons can be managed economically efficiently. For example, Trawick (2001) described one such system in the Peruvian Andes, in a peasant village where irrigation and water management are handled in an unusual way. Trawick analyzed the village principles of social organization, showing that these create a situation of equity and transparency which provides people with a strong incentive to obey the rules and use water economically efficiently. Ostrom *et al.* (1999) identified seven design principles for common property institutions that produce benefits that exceed costs. Moreover, these principles are versatile enough to be applicable to evaluation of institutions in most cultures around the world. (1) There must be clearly defined boundaries of the resource and of people with resource access rights; (2) Rules that govern the use of the resource and the required contributions of labor, material, time and money work for the local culture; (3) Political arrangements permit people with resource access rights to participate in changing the rules; (4) There is cheap and effective monitoring to identify each person's resource use; (5) Resource users who violate the rules face punishments that increase with the seriousness of the violation; (6) Conflict resolution mechanisms exist; (7) External government authorities recognize the rights of the resource users to organize.

4.13. Watershed councils

Watershed councils are composed of stakeholders who get together collaboratively to manage water and other natural resources at the scale of a watershed. As described by Burson (2000), there is increasing interest in using watershed councils to provide information for public natural resource managers. There is considerable variability in terms of watershed councils' goals, their effectiveness, stakeholder composition, their involvement in the real decision-making process, types of participation that are allowed, leadership, financing, decision-making procedures, economic efficiency and temporal scale. A similar analysis by Kenney (1999) identified a rapid growth of watershed councils in the 1990s. These councils are a response to historical and political trends that have resulted in increasingly ineffective forums and processes of resource management decision making and that have subordinated the role of local stakeholders in problem-solving efforts. In most cases, watershed councils provide a pragmatic vehicle for resource managers and stakeholders to address common concerns in a more economically efficient manner than is otherwise possible.

5. Conclusions: research challenges

Economic analysis has a considerable potential to improve economic efficiency, equity and sustainability in water resource policy. Still, difficult challenges remain. The following is a short list of challenges facing economic analysts who design decision support systems for water managers and policymakers; it does not pretend to be comprehensive:

- Designing laws and property rights systems for water that recognize legitimate historical uses, rewards current initiative, promotes reliable planning and subject those property rights to regulation in the public interest;
- Advancing cost–benefit analysis and better communicating its limits could better inform debates over the design and implementation of water policies and management actions;
- Designing programs that signal the marginal cost of water use, while protecting human rights for the most vulnerable;
- Improving the measurement of economic benefits of water programs through use of contingent valuation methods (CVM) would provide greater confidence that CVM-measured values reflect actual values held by individuals;
- Designing economic incentives that permit all parties to benefit from agreements for sharing trans-boundary waters;
- Building models that optimize an economic objective at the basin level that are testable, credible and useful for informing water policy decisions;
- Using economic principles to discover when demand reduction is a cheaper way to cope with shortages than supply expansion;
- Identifying economically efficient programs to finance reliable and safe access to water by the poor;

- Identifying cost effective methods to encourage the use of markets to promote water transfers while protecting third parties;
- Identifying thresholds that distinguish when it is more economically efficient to finance and deliver water services through public versus private measures;
- Identifying economic principles to establish criteria to support ecosystem restorations.

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