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The economic value of water in agriculture: concepts and policy applications ☆

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Abstract

The design of institutions that maximizes water's beneficial use in the face of growing demands for scarce and random supplies is the central policy issue in dry places. Information on water's economic value enables decision makers to make informed choices on water development, conservation, allocation, and use when growing demands for all uses are made in the face of increased scarcity. Conceptually correct and empirically accurate estimates of the economic value of water are essential for rational allocation of scarce water across locations, uses, users, and time periods. This review article raises several issues that must be considered in deriving accurate estimates of the economic value of water. These include establishing common denominators for water values in quantity, time, location and quality; identifying the point of view from which values are measured; distinguishing the period of adjustment over which values are estimated; and accounting for the difference between total, average, and incremental values of water. We illustrate values of water for agricultural use, based on a recent drought policy analysis of the Rio Grande Basin.

1. Problem

1.1. Background

The need to develop flexible institutions to maximize water's beneficial use in the face of growing demands for scarce and variable supplies is the most compelling issue for economic

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development for people who live in dry places. In most of the western US, surface and groundwater supplies are scarce and for practical purposes fully used. Rapidly growing human population and increasing demands for protecting endangered species and other environmental values are new uses of water. For political, legal, hydrologic, and economic reasons, it is likely that no region in the western US will develop new water supplies. New uses will have to be accommodated by surface water transfers from existing uses. Similarly, new groundwater appropriations are likely to require the retirement of surface water rights where ground and surface water flows are connected. In principle, more water, better timed water, water at a more suitable place, and better quality water for a particular use are usually available at a higher price if sufficient time is allowed for building storage, conveyance or treatment capacity. The nature of problems involving water is typically one of conflict among alternatives stemming from economic scarcity rather than physical shortages. The conflicts may be of various types. Examples include competition among kinds of uses, between geographic location of use, between current and future uses, between endangered species saved from extinction and food production displaced from saving the species, and between water resources developed or used and other resources displaced by that water development and use.

1.2. Relevance of information on the value of water

Rational decisions supporting water resource development, allocation, and use require measuring the value of water in alternative uses. When the market system works, markets allocate water and its related resources to activities yielding the greatest returns. Due to the high cost of capturing and holding water and because its supply is subject to a steady stream of unexpected changes, it is typically expensive or impossible to define, establish, and enforce property rights required by a water market system.[2] Therefore, well-defined market institutions that could generate prices that could serve to allocate water resources are typically lacking.

Decisions shaping water's development, use, and allocation occur mostly in the political realm and in other arenas outside the marketplace. Nevertheless there are many competing demands for taxpayer resources supporting water development and allocation and for the water itself; hence there is a compelling need for analysis in which the economic value of water proposals and plans can be compared to their costs. Controversy continues to erupt over water decisions in dry places of the world, particularly where emerging uses, such as endangered species, compete directly for water and money with more established uses like agriculture and cities. Despite these controversies there is often little time, money, knowledge, or will to conduct serious economic analyses of benefits and costs. While the people who propose moving, storing, saving, or cleaning water continue to change, economic principles for evaluating those proposals change more slowly.

It is easy to be overwhelmed by the wide range of benefits and costs claimed for water policy proposals; yet better understanding can currently only be obtained by consulting sizeable texts requiring considerable background in economic theory and methods of analysis. Few published works are briefly stated and widely-available that lay out economic concepts and methods that can be used to support water decisions. For these reasons, we believe an examination of economic concepts underlying the value of water is needed.

[2] Ciriacy-Wantrup (1967), Young and Gray (1972), and Griffin (1998) elaborate.

The objective of this review paper is to provide useful information for these debates by synthesizing modern economic principles on the measurement of economic values related to water policy decisions and on the use of these values in the conduct of cost–benefit analysis.[3] Two approaches are used. The first is to review the economic theory needed to support a conceptual framework for establishing economic values for water which can be used by policy analysts interested in proposals that would affect public or private water development, allocation, and use. The second method is to illustrate the range of economic values of water for agricultural use, the major water user in most dry places, such as the western US.[4]

This paper only addresses values defined as economic benefits from uses of water. Questions relating to evaluation of water resources for other social purposes, such as income redistribution, regional economic development, or environmental quality, are beyond the scope of this paper.

2. Economic theory

Water has economic value only when its supply is scarce relative to its demand. Whenever water is available in unlimited supply, it is free in the economic sense. Scarce water takes on economic value because many users compete for its use. In a market system, economic values of water, defined by its price, serve as a guide to allocate water among alternative uses, potentially directing water and its complementary resources into uses in which they yield the greatest total economic return.

In dry places, economic and population growth create situations where water is economically scarce. In these places, water institutions, laws, projects, policies, and programs are designed to provide for maximum benefits from the use of scarce water. Not only is water itself scarce, but money, manpower, and other resources required to develop, allocate, transport, and purify water are scarce. Competing claims for money and other resources and the economic and political difficulty of increasing taxes to pay for water programs constrain the resources available for water programs. While the political process always determines which programs are undertaken, there is

[3] A similar work was done by Wollman (1962), who valued alternative uses of Colorado River water then recently allocated to New Mexico. Young and Gray (1972), to whose pioneering work we dedicate this paper, identified economic concepts and empirical values of water. Bergstrom and Dorfman (1994) estimated the value of groundwater quality protection. Freeman (1995) examined economic values of water quality improvements for marine recreation. Frederick, Vandenberg, and Hanson (1996) studied economic values of freshwater for four withdrawal uses and four instream uses in the United States. Griffin (1998) reviewed the literature on cost–benefit analysis of water programs.

[4] Environmental and municipal uses and values of water continue to increase in importance. In some cases, endangered species have moved to the top of the list in the competition for water in western river basins. Several recent studies on environmental values of water have been published. A few examples include values of fisheries by Barbier (2000), wetlands by Acharya (2000), groundwater recharge of wetlands by Acharya and Barbier (2000), oceans by Costanza (1999), endangered salmon by Huppert (1999), recreation by Ward and Beal (2000) and Fadali and Shaw (1998), instream flow by Willis and Whittlesey (1998), environmental compliance by Naeser and Bennett (1998), conservation by Goodman, Seabrooke, and Jaffry (1998), groundwater protection by Stevens, Barrett, and Willis (1997), marine recreational fishing by Bell (1997), water quality improvements by Choe, Whittington, and Lauria (1996), amenity values of rainfall by Englin (1996), riverside wetlands by Kosz (1996), estuaries by Kaoru, Smith, Kerry and Long (1995), and forest wetlands by Swallow (1994).

also a need for more general economic standards by which competing water policies and programs can be gauged.

The economic principles underlying water policy decisions rest on the ideas of benefit and cost.[5] For example, releasing water from a dam to increase streamflow by 100 cubic feet per second may add 500 units of endangered species habitat, which, for example, might be worth $25 each. The benefit of this policy will be $500 \times \$25 = \$12{,}500$. According to the basic rule of benefit maximization, in which increasing the total value of scarce resources is presumed desirable, this action should be undertaken if its cost is less than or equal to $12,500. All the additional costs resulting from a proposed action are its marginal costs, and the extra benefits are its marginal benefits. If enacted policies are limited to those that increase economic efficiency, a water program will only be implemented if its marginal benefits equal or exceed marginal costs.[6] For public water policy proposals, maximum beneficial use of water and its complementary resources requires that government formulate, implement, and evaluate their program plans and select their programs using these economic principles. An important aim of water use in dry places can be stated in terms of maximization of the product or revenue obtained from that water use. What is to be maximized is the social benefit from the water used and not the quantity of water used itself.[7] In areas of intense competition for water, an important objective of water allocation policy, in addition to protecting the public interest, is to allocate the water resource to those agricultural, residential, industrial, recreational, endangered species, and other uses that will make the most productive use of the water available for these purposes. Put differently, this goal is that water institutions and programs should help shape civilization along lines desirable to those people who use the water by increasing their living standards.

While the principle of maximizing the total economic value of resources such as water is an essential concept of modern natural resource economics, there is considerable debate among water policymakers and the public at large on how this can be achieved. In principle, one could examine a given river basin with known potentials of water use and look for that use or combination of water uses which produces the greatest economic product from a given expenditure of goods, services, and water.[8]

State and federal legislative bodies, when designing water institutions, attempt just this, subject to an acceptable distribution of these benefits. So we will see continued policy debates over the quantity and quality of water available for all major uses and heated discussions regarding the best allocation among uses of water and among competing proposals that would alter those uses.

[5] Benefit–cost analysis for government water programs were developed for the US Congress in several attempts to isolate a water projects's economic performance from its political support. Examples include US Bureau of the Budget (1952), US Congress (1962), US Interagency Committee on Water Resources (1958), and US Water Resources Council (1973, 1979, 1983). More recently the Environmental Protection Agency has developed economic standards for evaluating proposed environmental programs and regulations. Recent reviews of the economic theory underlying the economic valuation of water include Merrett (1997), Molden, Sakthivadivel, Perry, de Fraiture, and Kloezen, (1988), Molden, Sakthivadivel, and Habib (2001), and Perry (2001).

[6] This is the equi-marginal principle. If economic efficiency is important, it should be applied to whatever is the smallest quantity over which decisions are made and data can be made available. It should also be to all incremental decisions in the nation, whether they are made by private business or public action. For the case of a private business, needs of income maximization require firms to follow the equi-marginal rule.

[7] Trelease (1965) made this distinction.

[8] River basin analysis was the motivation behind the work by Wollman (1962).

Translation of the physical effects of a proposed water program or policy into economic benefits and costs involves estimates of the values of the increases and decreases in goods and services under future conditions *with* and *without* the program.[9] For purposes of economic analysis, benefits and costs should be measured from the same viewpoint (private, local, regional, national), same period of time, and for the same program aims. Starting with estimated physical effects of the proposal, it is necessary to evaluate those effects in monetary terms. Market prices for program outputs are a good place to start in the search for an estimate of their economic benefits; but as will be discussed subsequently, many adjustments may be required. The effect of all this is to express benefits and costs of water programs in monetary terms reduced to a common denominator for comparison.[10]

In the field of public water policy, analysis of benefits and costs uses a simple decision rule. If, for some proposed action, the sum of benefits exceeds the sum of the costs by a larger amount than any other action with the same aim, the proposed action should be adopted. Otherwise it should not.

For the concept of revenue to the private firm, one substitutes the concept of benefit to society. For the cost to the private firm, the concept is opportunity cost. Opportunity cost is the value of benefits displaced by a policy action that diverts resources from other productive economic activities and brings those resources to support that action. For the firm's profit, one substitutes the concept of the amount by which benefits exceed costs to the larger society.

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[9] That is, the 'with and without' principle should be used. This means we should compare benefits and costs *with* the water proposal compared to benefits and costs *without* the plan. Applying this principle tells us the outcome from choosing the policy compared to what would happen by not choosing it. By contrast, it is a mistake to use the 'before and after' principle, which compares what happens before and after implementing the policy. For example, one could mistakenly evaluate the world-famous Las Cruces New Mexico Flood Control Dam project using the before and after principle. Mistaken use of this analysis would conclude that before building the dam there was a terrible flood in Las Cruces; but after its construction, Las Cruces has been flood-free. However use of the correct 'with and without' principle shows that there has been too little rain to cause a flood even without the dam, so the 'with project' results are no different from the 'without project' results. Analysts who use the before and after principle reach the false conclusion that building the dam was good economics. Those who use the with and without principle correctly find that building the dam has produced negative net economic benefit to date.

[10] For the market system to allocate water in society's best interest, several conditions must occur. One requirement is that water resources be mobile, i.e., free to move to those activities which yield the greatest return. If, in fact, water resources are not mobile, market prices cease to reflect the resource cost, since the opportunity cost of unused water is zero. A related common problem in water management is the problem of less than full use of existing water. If unused water is widespread, even highly mobile and available water cannot make market prices of water convey useful information, since there are no alternative uses for unused water. Private economic efficiency, as a yardstick for evaluating water proposals or plans, is defined as total private revenues minus total private costs. The use of efficiency as a standard for formulating, carrying out, or implementing water policies is subject to intense criticism, because any number of alternative development schemes may satisfy the criterion. For example, an irrigation project may make irrigation water users richer than any alternative project, while a power project may make power users better off than any other alternative. Both projects are therefore efficient in the sense of private net income produced by water. These limitations have caused economists to expand the traditional definition of private economic efficiency and to value water resources by means other than market prices.

2.1. Defining the economic value of water

The economic value of water comes from the many uses to which water can be put in satisfying people's needs. Water can have a very high economic value because it is scarce and because it is capable of being applied to many different uses. As a consumer good in ordinary households, water is needed first to drink, then for cooking, then for toilets and bathing, then for cleaning things like clothes and dishes, next for washing cars and driveways, and finally, in dry regions, for landscape irrigation. In the summertime in dry regions, by far the largest use of water in households is for outdoor irrigation.

In discussing the economic value of water, we begin by posing the question of how well the price actually paid for water accurately represents the benefit that arises from its use. The price that a person pays for water can never exceed and seldom comes up to that which he would be willing to pay rather than go without it: so that the economic benefits a person gets from the use of water typically exceeds that which he pays for it.

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 for it.[11] 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, people will only use water for irrigating their lawns or for low-valued crops if the price of water is suitably cheap. At a high water price, neither of these uses produces a high enough economic value to make it affordable.[12]

2.2. Dimensions of water use

Quantity supplied is only one dimension of water use. In addition, time utility of water use can be improved by building dams and developing groundwater reserves, while location

[11] Defining value in this way assumes economic efficiency is the objective. More generally, the benefits attributable to a proposed water policy have meaning only in relation to the objective and are measured as the contribution of the resource to the objective (Marglin, 1962).

[12] That is, an efficient water price assures that expensive water is not put to low-valued uses. But a fair price of water is defined as a price for basic needs everybody can afford to pay. Depending on the country, context, or culture, the fair price may be as low as zero for the first few gallons daily. Political experience has shown its important to keep the price of essential water uses cheap. Tucson, Arizona experimented with marginal cost rates for water, after the 1976–77 drought. One year after adopting these rates, the entire city council was voted out of office.

One method for pricing water fairly and efficiently is 'politically feasible marginal cost pricing' in which basic human needs are priced cheaply, while luxury uses are priced at a level that reflect the real cost of water. Accomplishing both is particularly important in drought periods in which wasteful water uses divert water from basic human needs. A good example is a policy experiment recently conducted by the Metropolitan Water District of Los Angeles, described by Hall (2000). Several US cities currently use an increasing block rate water pricing policy, in which higher prices per thousand gallons are charged as greater total volumes of water are used. The lowest bracket of water use is priced so that minimum per capita household water requirements can be met cheaply, even for the lowest income households. By this system, homes are equitably supplied with the basic requirements for drinking, cooking, and hygiene, while incurring higher costs for use beyond that which is considered the minimum daily requirement.

utility can be improved by building water transport systems such as aqueducts to move water to places far from its natural source. Next, location utility itself is measured in three dimensions (depth, input price, and efficiency), since ground water is increasingly expensive to put to beneficial use with increasing depth and increased energy prices, but is cheaper with increased 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.

The point of discussing these four dimensions of water is that balanced public or private water policy decisions will consider all four dimensions of the economic value of water. Ignoring any of the four dimensions produces policies that may fail to improve human welfare.[13]

2.3. *Defining water use*

Water is different from other scarce resources. Water use for one purpose at a given time and location does not necessarily displace its use elsewhere, or at a later time for the same or another purpose. A single water molecule is typically used many times as it moves downstream. The re-use potential of water is an important consideration for water administration, especially where water rights are transferred and where third-party effects associated with the transfer are significant.

An important water valuation problem is that of choosing the unit of measure for the quantity of water used. In certain situations, such as complementary water uses like high mountain recreation and hydroelectric production, evaluation of water resource development decisions may not require a measure of value per unit of water used. This is true only as long as one use does not displace another. But where two or more uses compete, such as instream flows of water for endangered species habitat competing with water for agriculture, a measure of water use is required to express economic values in a common denominator. The typical choice of the appropriate measures of use is between withdrawal and depletion.

One argument for measuring use in terms of water *withdrawn* from a stream is that withdrawal is what the individual private user typically pays for and receives the use right where water rights are transferred. Measures of consumption in terms of net stream *depletion* may be misleading. For example, return flows from irrigation through saline soils may so degrade the water quality as to make it unusable. Similarly return flows seeping to the groundwater table in a deep aquifer may not be economically available for reuse in any practical planning period. Where instream flow uses compete with each other, such as maintaining a natural variable flow pattern for endangered species habitat versus keeping high steady flows for stocked trout, neither of these units of use may be useful. In this case, using the 'with and without' principle described earlier is the most reliable method to reach a benefit-maximizing decision.

[13] Water quality issues continue to grow in importance. For example, downstream users in both the Colorado and Rio Grande basins have faced salinity problems for years. Because salinity levels were not explicitly dealt with in either the Colorado or Rio Grande Compact, upstream users have been reluctant to incur costly investments which would reduce downstream salinity, even where total benefits may considerably exceed total costs. The problem is that upstream users' benefits would typically be much less than upstream users' costs. Transactions costs accompanying water pollution control programs are also important, as described in McCann and Easter (2000).

2.4. Amount of water valued

The most basic distinction among the various economic concepts of value are those relating to total, marginal, and average value. The *total* value from a given supply of water is measured by the total willingness to pay for a given level of water used.

The *marginal* value of water represents the contribution of an incremental unit of water to whatever public or private objective is under consideration. We illustrate the concept for both the public and private uses of water with an example. Holding back one extra acre-foot of water at a small reservoir to prolong the recreational boating season by a month in August may contribute ten extra boating days for the month. If boaters could be charged $30 per additional boating day, then that acre foot has a marginal value of $300 as a recreational boating resource. If the same added one acre foot saves $200 in costs associated with cotton yields otherwise lost, then the water's marginal value in private irrigation is $200.

The *marginal* value of water provides important information for policy analysis of water development or allocation. For the development case, decisions dealing with increased water supply, economic efficiency requires that water development be expanded as long as the marginal value of the added capacity exceeds its marginal cost. That is, if the marginal value of expanding a water system's capacity is greater than its marginal cost, then it is good economics to expand the system. For the allocation decision, the allocation of scarce water among competing uses, economic efficiency occurs only when marginal value per unit of water is equal for all uses. That is, policies improve economic efficiency when they reallocate water among users if the marginal value gained by the gainer exceeds the marginal value lost by the loser.

The *average* value of water is the *total* value described above divided by the quantity of water supplied. The average value of water is typically of less policy interest for water allocation than marginal or total value, but its conceptual simplicity and ease of calculation may engage the policy analyst into using it to approximate marginal value. Since average value is typically much larger than marginal value, use of estimated average value, when marginal value is the needed measure, usually leads to an over-investment in water supply capacity or over-use of water.[14]

2.5. Targeting values to policy issues

What has been called the 'average versus marginal fallacy' applies the average value of water to policies that require information on its marginal value.[15] The fallacy is to divide total gross regional economic product by total water use, then argue that this number is the value of additional water per acre foot brought into a region or the economic benefits of policies that save it from facing shortages. Examples of such policies include new surface water development to compensate for groundwater overdraft, meet water demands for growing cities, or meet instream flow requirements for endangered species' critical habitat.

The following example illustrates the misuse of average values of water for policy analysis. New Mexico policymakers may wish to know the economic worth of a policy that supplies new water

[14] An excellent discussion of total, average, and marginal values of water is in Young and Gray (1972).
[15] A classic study was done by Martin and Young (1967).

to the state. Total income from all sources in New Mexico's Rio Grande basin is about $26 billion per year[16]. Total annual surface water use in New Mexico's Rio Grande Basin in a normal water supply year is about 500,000 acre feet. So the average economic benefit to New Mexico per existing acre foot of water used in agriculture is $26 billion divided by 500,000 acre feet, or about $52,000 per acre foot. While $52,000 per acre foot is the correct *average* value per acre foot of existing water used, it is many times higher than the *marginal* or additional income from new water, if made available. If new water could be supplied to New Mexico, through weather modification, reduced evaporation, irrigation conservation, or importation, little if any will be used by cities. Cities buy existing water rights from farmers at a far lower price than the cost of finding new water. Moreover farmers will avoid taking pecan trees out of production if they reduce their water use in agriculture. Given a choice, farmers will reduce their water application on their lowest valued crops in terms of net income produced per acre foot consumed. These crops are typically cattle feed, such as irrigated pasture or alfalfa.

Compare the misuse of average values to the correct analysis of marginal values for policy analysis. The marginal gain from added water is what farmers could be charged per acre foot of water to apply that new water to cattle feeds grown with the new water and still stay in business. That is, the marginal value is their willingness to pay for the added water. Based on actual prices charged to farmers for surface water, this marginal value is typically somewhere around $16[17] per acre foot, as of the year 2001. So additional water brought to agriculture is worth about $16 per acre foot, not $52,000. This simple comparison illustrates clearly why average values of water can be much higher than marginal values.

2.6. Technology improvements

Technical change affects all water users, especially in agriculture where crop yields have historically increased in the face of newly developed crop varieties. Technical change can also affect residential water users when there are new developments in water conserving devices, such as low flow toilets, low flow showerheads, or new developments in xeriscaping, a method of landscaping that saves water by substituting desert plants for lawns.

Analysts should guard against assigning benefits of technological advance as if they were benefits of water programs. Assigning a higher value of water to advanced technology violates the 'with and without' principle. This assignment double counts benefits which should be credited only against investment in research and development. Moreover, technological change has historically increased crop yields and reduced food prices. It is an error to credit technological advances as benefits to water without also incorporating commodity price decreases which reduce farm incomes. Advances in technology increase the productivity of water, but these advances are not values of water, they are values of technology.

[16] US Department of Commerce, Bureau of Economic Analysis, May 2001.

[17] A recently completed study of the Rio Grande Basin found that the value of extra income produced by the last acre foot of water in commercial farming is about $9 per acre foot when full surface supplies are available (Ward et al., 2001).

2.7. Increased vs. decreased supplies

The economic value of a given reduction in the water supply is larger than that of the same increase for two reasons. First, reducing the supply of water reduces quantity demanded, limits water use to higher-valued uses, and results in a higher water price. For example, agricultural water rationing in a drought that reduces water use by 20% imposes a much higher damage than the same users would gain from a new reservoir that increased current use by 20%.

Second, the value of water lost by decreasing water supplies should include a measure of the value of the long run investments in facilities that producers would lose. For example taking 1000 acre feet from irrigated agriculture permanently to supply water for endangered species critical habitat may require producers to take 500 acres out of permanent production and lose total incomes valued at $300 per acre, for a total of $150,000 in net producer income lost. But adding 1000 acre feet, especially if unplanned, may produce zero extra net income since producers may not be able to use it.

2.8. Large supply changes

Some water development projects or programs are large enough to affect the national supply and price of crop or livestock derived from the added water brought to a region. Good examples are water policies directed at mitigating the costs of climate change or drought that would affect national food or fiber markets. Policies that alter electric power generating capacity from building (or removing) major dams in small countries or policies that remove water from crop production for endangered species are other examples. In such cases, the value of water must include price changes in the final output produced by the water, so that demand functions for commodities replace fixed commodity prices.[18] For example, a drought coping policy that increases reservoir storage in a major agricultural producing state like California could reduce national prices of cotton, dairy products, and produce, and would produce a national benefit far greater than the California farm income gained.

2.9. Physical interactions in use

Physical interdependence among various water uses complicates evaluations of benefits and costs of proposed programs that change existing water use patterns. Any single water use cannot typically be viewed in isolation from potential alternative uses. The typical river basin contains several alternative uses for water, any one of which may affect others through any or all of the quantity, quality, time, and location dimensions.[19] As a general principle of valuation, the benefits

[18] By demand functions, we mean a mathematical formula that summarizes how a commodity's prices changes with changes in the quantity of the commodity available that is produced by the irrigation water. The demand function for pecans shows how national pecan prices are determined by total pecan supply.

[19] Young and Haveman (1985) explain. Suppose water is retained at a high elevation reservoir to provide for urban peak power requirements in mid-summer or to keep water in the channel downstream for endangered species habitat. But, holding water upstream for power or habitat may substantially reduce the quantity available for irrigation use downstream late in the growing season, when short-run irrigation values can be several hundred dollars per acre foot to prevent a total crop loss. Another example is a proposal to release water from large upstream reservoirs in a severe drought to maintain downstream navigation traffic several hundred miles away. Upstream recreation values displaced are the costs of maintaining barge traffic.

from a particular increment of water supply in a given location in a river basin is the sum of the values produced in the first location and the value of all altered return flows in all subsequent uses, locations, and time periods.[20]

2.10. Establishing common denominators

Because of variability in quality required for alternative water uses (e.g., irrigation vs. endangered species habitat vs. residential vs. manufacturing), one common denominator for specifying quality is raw untreated water flowing in the stream. Both treatment and transport costs must be subtracted from the value of the water at its offstream use location in order for values in these uses to be comparable to values for other uses. For example, suppose untreated water in the stream is worth $35 per acre foot to support a blue ribbon trout fishery and that transport costs are $10 per acre foot to move the water from that stream onto a farmer's chile field. If the on-site economic value of that water for growing chile is $40 per acre foot, the instream equivalent value for that chile is $40 minus $10 = $30. The comparable values become $35 for trout habitat and $30 for chile production.

Barriers to measuring common denominators for water's value continue to fall with the introduction of fast personal computers and improving mathematical programming software. Both the machines and software have facilitated the development of dynamic mathematical models of the hydrology, biology, economics, and institutions which can encompass the quantity, time, space, and quality dimensions of the problem simultaneously. Some modern software[21] enables analysts to write algebraic functions that express irrigation, hydropower, municipal and industrial, recreation, and endangered species demands as mathematical functions over the dimensions of quantity, quality, time, and location. With numerical expressions of 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 total beneficial use of water.

Overall, several economic and hydrologic factors affect the value of water. These include which sector uses the water, the type of product supplied by the sector, the demand for the water's final product, the on-site productivity of the location where the water is used, the level of complementary resources at the site (such as reservoirs and irrigation facilities) and transportation, storage, and processing costs for off-stream uses. For example, designer bottled water in grocery stores priced at $1 per quart has an economic value of $1.3 million per acre foot.[22] At the other extreme, when a river basin's reservoirs are full and lacking storage space, aquifers are full, soil is saturated, and crops are already planted and irrigated, then 40,000 added acre feet of June snowmelt has a highly negative economic value.

[20] The total net value of a proposal is measured by netting out the positive and negative effects which occur elsewhere, in a future period, or in different locations (Brooke, Kendrick, and Meeraus (1992); RiverWare (2002)).

[21] Two examples of which we are aware include the General Algebraic Modeling System, GAMS Development Corporation, Washington, DC, and RiverWare, Center for Advanced Decision Support for Water and Environmental Systems at the University of Colorado at Boulder.

[22] There are 4 quarts per gallon $\times$ 325,851 gallons per acre foot, or 1.3 million quarts per acre foot.

3. Methods of analysis

Where a service, such as water supply, is exchanged in a functioning market, its market price is a good measure of its marginal value. For the case of water, we address two kinds of market transactions, free market prices and administered prices, in addition to one type of non-market transaction, the change in net income.

3.1. Market prices

Market prices for water offer an opportunity to observe water's economic value directly. Nevertheless, where market transactions are recorded, analysts should use this price with care to avoid misinterpretation. 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 (Ward & King, 1998; California Department of Water Resources, 1992). The water right owner maintains the title to the annual water use but sells, rents, or leases his 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.

Permanent water rights transactions occur in many dry places. 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 includes water, land, and facilities. The observed transaction price of unrestricted transfers between similar water right users is the correct measure of the long-term private value of the water used for that purpose.[23]

3.2. Administered price

Water supplies are often sold under what amounts to an administered price. Good examples are irrigators who pay a fixed price per unit of use to an irrigation district or homeowners who buy water from a public or private water utility at a set price.

If the water buyer is free to adjust his use to meet his needs at the specified price, then statistical analysis of data pertaining to the relationship between water consumption and price can be to measure the economic value of water to the final user. However for this method to work, historical administered prices must vary and water buyers must have been permitted to freely adjust their demand to price changes. If the water user faced an upper bound restriction on water use (such as a 3 acre foot per acre upper limit in irrigation or summer lawn watering restrictions to homeowners) or if water use is not permitted to increase with falling prices, then this method does not work. Furthermore, this value has to be adjusted for costs of water transportation, storage, and water treatment to make it comparable to instream values of raw water.

[23] However, analysts still need to guard against possible errors. If the water right has junior standing in places where seniority is important like Colorado, USA, and does not receive a 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 may not depend on a given volume of water in the river in a given period.

In the American west, prices are usually charged to individual users of water for irrigation for water supplied under federal reclamation projects. These prices are typically set by Congress to be much less than the incremental costs of supply. Still, these prices are accurate estimates of short-run marginal value if a user may purchase all quantities desired at that price.

The more common situation regarding water use at the low price is that the water right sets an upper limit of water use and this limitation constrains the irrigator to use less than he wishes to purchase and apply to crops. Pecan growers in southern New Mexico and West Texas are an excellent example of this situation. Pecans are a high-return but thirsty crop. A pecan irrigator may be able to find surface water at $16 per acre foot from an irrigation district for each of the first 3 acre feet purchased; but at that price, may wish to apply 6 acre feet of surface water per acre per year to the trees. If only 3 acre feet of surface water are available, then the $16 per acre foot price of surface water is much less than its marginal economic value.

3.3. Change in net income

Where water is an intermediate good,[24] such as in crop irrigation, hydroelectric power used in manufacturing, or water-based recreation, the demand 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. This change in net producer income also measures the gain in additional consumer satisfaction from the final product minus the added costs of delivering that satisfaction.

3.4. Measuring productivity

Economic benefits from increases or decreases in water allocated to irrigation are measured as the change in value of agricultural products less changes in associated production costs.[25] Despite this simple concept, establishing values for irrigation water presents several practical problems. As is the case with water generally, market prices for irrigation water are rarely available so estimates of value must often be based upon indirect approaches.

Methods of valuing irrigation water typically rest on observing the response of crop yield to various water applications, that is to the change in yield due to a change in water applied. However, several barriers make it difficult to obtain accurate measurements of this relationship.

First, crop production under irrigation is applied in uncontrolled and unpredictable environments. Output, even under experimental conditions, may vary significantly with soil type, fertility, temperature, and rainfall. Furthermore, irrigation decisions are made by a large number of individual farmers, each representing a small percentage of the total irrigation water used; and these farmers vary widely in management abilities, experience, scale of farming operation, willingness to bear risk, and financial constraints.

Next, crop yield response to water application depends strongly on the rate at which water is used with other inputs in each of many time periods. Quantities of soil nutrients, seeding rates,

[24] An intermediate good is a resource used in production, valued not for the direct satisfaction it provides consumers, but only as an input to a final product that brings satisfaction to final buyers.

[25] This concept was developed by the US Interagency Committee on Water Resources (1958).

climate, and daily weather fluctuations are especially important. If water is the limiting resource, additional water applied increases yields by much more than if other resources are limiting. Each crop in a producing area has a unique physical productivity with respect to irrigation water. Further, for any crop, there are a number of varieties available and each may respond differently to the water applied and to the water's quality.

In addition, technological change has important effects on the value of water. As crops are improved over time, increased yields produced by the water increase the water's economic value. If crop varieties are developed that permit fresh produce to be supplied and marketed in a place where only cattle feed was historically grown, the value of water in agriculture can increase considerably. Likewise, successful development of drought or salt-resistant crops can increase the economic value of water in places that have saline water (e.g., the lower elevations of western river basins) or are prone to recurrent drought. Crop response to water is greatly limited by water salinity levels. The development and installation of effective drainage systems, while often expensive, can still increase the economic value of water in agriculture considerably.

Last, we examine the production response to irrigation water. A production function relates water input to crop output. Application of this method requires recognizing that irrigation water productivity varies widely over the year depending on soil moisture and the plant's growth stage. When soil moisture in the plant's root zone is already at maximum level, plant response can be zero or negative. The productivity of added water applied to the plant increases with the time interval at which the last moisture occurred. As soil moisture is reduced and the productivity of added water depleted, a point may be reached at which the crop would be completely lost if an irrigation failed to occur. Water applied at this critical time is extremely valuable economically. The value is the net income loss avoided by the application of irrigation water. The point of all this is that the crop yield irrigation water relationship is highly region-specific and depends on the timing of the water applications over the irrigation season, on existing rainfall patterns, and on other local conditions.

3.5. Crop water relations

Estimating the change in net income produced by water applied to crops requires an estimation of the impact of added water on physical crop production, and requires good agronomic data. The most reliable data are derived from direct observation of the response of crop yields to water applied and are based on controlled experiments. Experiments such as these are expensive, difficult to generalize to soils and climates different from the experimental area, and for those reasons, scarce.[26] Moreover many doubt the direct transferability of experimental results to on-farm field conditions.

For these reasons, other procedures have been used. These include field surveys that characterize the experience of farmers or surveys of specialists such as crop researchers or extension agents. While these people are typically well prepared to say which crop outputs have been associated with what water inputs historically, they are typically unwilling or unable to

[26] One exception is the work edited by Steward and Nielsen, for example the chapter on corn by Rhodes and Bennett (1990).

generalize beyond historical experience. So data needed to fit a production relationship characterizing the crop yield response of timed water applications and timed applications of other inputs typically do not exist.

Several indirect approaches are used. The Blaney–Criddle[27] technique and its updates (such as Doorenbos & Pruitt (1975, 1977)) and several others described by McKenney and Rosenberg (1991) presume that each crop has a unique evapotranspiration (ET) requirement. This requirement is associated with the water application that achieves maximum yield, and this yield for many crops is a linear function of ET. This ET depends upon climate and the crop itself. A formula is used which can be adjusted to provide for any crop the water requirements for any given climate specified.[28]

These methods typically do not permit water to be combined with other resources in variable proportions. Still they provide a single point on a production function which relates a single quantity of water used with a single level of crop output. One interesting approach for simulating crop-water production functions is to begin with maximum crop yield for a full water supply and estimate impacts of crop deficit irrigation by considering reduced ET combined with an assumed physical process model of yield deficit associated with various levels of deficit irrigation. Good examples are provided by Lety, Dinar, and Knapp (1985), Lety and Dinar (1986) and Dinar, Knapp, and Rhoades (1986), Dinar, Rhoades, Nash, and Waggoner (1991). The advantages of this method are that it provides an affordable alternative to costly experiments and it can be applied to a wide range of crops that have similar underlying soil-water-yield physical properties. A disadvantage is that it may poorly predict actual yields in extreme conditions. The point of this section is to show the importance of having good crop-water response data for measuring the economic value of water in agriculture, and to illustrate the difficulties in finding those data.

3.6. Period of adjustment and accounting stance

Two factors have a large influence on the economic value of water. The first is typically termed length-of-run, i.e., planning period over which resources are committed and their costs sunk. Sunk costs are all costs incurred in the past that cannot be changed by any future decisions. For any water policy planning period in which costs are sunk, these costs can be ignored in the policy decision. The economic principle behind ignoring sunk costs is to let bygones be bygones, not to look back, since sunk costs cannot be avoided or recovered through a future action. The relevant decision is to calculate the added costs incurred by a proposed action and to weigh these costs against the action's added benefits. The same principle says to ignore all costs and benefits that occur both with and without the proposed action and make the decision based only on changes in costs and benefits the action produces. Carrying out this economic principle in the realm of practical water policy means that the period of adjustment needs to be defined. Three common periods of adjustment are the very short run, the short run, and the long run, discussed subsequently.

[27] Blaney and Criddle (1962), Determining Consumptive Use and Irrigation Water Requirements, USDA Technical Bulletin, 1275 (1962).

[28] Jensen, Burman, and Allen (1990) summarize the state of the arts.

The second factor that influences the value of water is the accounting stance, i.e., whose values should count. This paper considers two stances: the private and the national view.[29] These two dimensions over which water's value changes produce six classes of value described in more detail by Young and Gray (1972), four of which are discussed below.

3.6.1. Private very short run values

This value of irrigation water is based on water applied within a single irrigation season, after the crop is already planted, and after production is taking place. For this case, land preparation, planting, fertilizing, labor, and tillage costs are already sunk and cannot be retrieved once they're committed. If the crop would be lost in the absence of post-planting irrigation, the irrigator will pay for the water up to the market value of the crop saved minus all post-planting costs of production. Very short run values of water ignore all capital, pre-planting and planting costs, and associated labor; because after planting occurs, these costs are sunk. Since these costs are ignored in computing very short run values, these values of water are higher than either short-run or long-run values. Very short run values of irrigation water equal the total gross value of the crop produced by irrigation minus all post-planting costs.

3.6.2. Private short run values

The private short-run value of irrigation water is based on the pre-season choice of what crops to plant and how much water to apply to each over a crop season. Land, buildings, equipment, the system distributing water, prices and technology are fixed and cannot be changed in the short run. Water is allocated by the farmer over this period using the objective of maximum private short-run net income. Net income, for the short run is additions to revenue minus addition to short run costs.

3.6.3. Private long run values

The long run period of adjustment is the planning period in which the farm operator decides whether or not to keep the land in farming. There may be several reasons for taking irrigated farmland out of agriculture altogether. Examples include selling agricultural land and water to growing cities or selling the land to real estate developers for roads, houses, commercial buildings, or apartments.

The private long run value of water is defined as the net added income produced by a given increment of water supply after subtracting all long-run production costs. All non-water resources are variable and must be paid at a price equal to their opportunity costs, or they will leave agriculture and migrate elsewhere.[30]

The unit of land, equipment, buildings, and associated water becomes the marginal unit of input for which the decision to stay in farming is made. In this case the marginal economic value of water is its average value productivity, defined as total long-run income divided by total water applied.

[29] Others that have been used include the local, regional, and global views. Howe (1987) argues persuasively for the global view.

[30] That is, costs from using these resources are all avoidable and will leave agriculture if unprofitable.

3.6.4. National long-run values

The principles described in the previous three sections regarding the economic values of water apply entirely to a private producer's view in which agriculture operates in a competitive environment. As part of that environment, no single farm significantly affects the price of agricultural products or the price of resources used to produce those outputs. It is also presumed that there is minimum intervention from the government in the marketplace. Irrigated agriculture operates under a wide variety of incentives, rules, regulations, and constraints set up under various levels of public action.

The relevance of these points for measuring national long run values of irrigation water lies in the impacts of government supported output and input prices. The major difference between long-run private value and long-run national value of irrigation water rests with the fact that the social values require estimates of the social value of farm commodities and inputs. Because the national value of irrigation water is typically lower than the private value, because of unpriced costs imposed by irrigation on the larger society, private values are an upper bound estimate of the social value.

3.6.5. Defining a water policy

Economic values are assigned to proposed changes in policies in institutions compared to the status quo. We assume any of these can be expressed as equivalent changes in the supply and/or price of water available to irrigated agriculture. Three contemporary policy examples relevant to the western United States include setting aside critical habitat for an endangered species, subsidies of agricultural water-conserving measures, or a stream adjudication that clears titles to water rights. Each of these actions would reduce the supply of water and/or increase the price to farmers. Results without the policy are expressed as a high water supply, and those with the policy are from low supply.

3.6.6. High supply

Based on conditions facing the farmer and the choices made shown in Tables 1 and with more detail shown in Table 2, the total value of surface water, $95,000, represents the farmer's annual total willingness to pay for the 1500 acre feet per year of surface water delivered to and used by the farm. Total value is net income plus the water bill. The maximum possible value of surface water income is defined as maximum annual income earned with surface water ($102,500) minus maximum net income possible with groundwater only ($30,000), $72,500. The $102,500 surface water income is computed as total revenues per acre minus total costs per acre times the number of acres farmed (Table 2, top row).

3.6.7. Low supply

The low water supply condition is also shown in Table 1. The total value of surface water, $46,000, is the farmer's annual total willingness to pay for the surface water, $10,000 net surface water income plus the $36,000 water bill. This considerably higher surface water bill is based on 1 acre foot per acre of surface water used averaged over the 500 acre farm. Total value of surface water ($46,000) is net surface water income ($10,000) plus the water bill ($36,000), shown in Table 2, bottom row.

Table 1
Conditions facing and choices made by a hypothetical irrigation farmer

	Background conditions	
	High water supply	Low water supply
Surface water price ($/ac-ft)	18	72
Surface water supply (ac-ft/ac)	3.0	1.0
Other conditions	Table 1B	Table 1B
	Choices made	
Surface water demand (ac-ft/ac)	2.5	1.0
Groundwater demand (ac-ft/ac)	0.0	1.5
Unused surface water (ac-ft/ac)	0.5	0.0
Unused groundwater (ac-ft/ac)	3.0	1.5
Net total income (500 acre farm)	102,500	40,000
Net groundwater income (500 acre farm)	30,000	30,000
Net surface water income (500 acre farm)	72,500	10,000
Surface water bill (500 acre farm)	22,500	36,000
Total value of surface water (500 acre farm)	95,000	46,000

ac-ft: acre foot; ac-ft/ac: acre foot per acre.

With the now higher surface water price and scarcer surface supply, the rational decision is to farm 400 acres produced under half-surface-half groundwater (1.25 acre feet per acre from each source) and 100 acres produced with groundwater technology (2.5 acre feet per acre of groundwater). Over all 500 acres, this averages out to 1 acre foot per acre surface water and 1.5 acre feet per acre groundwater.

3.7. Valuing the water

3.7.1. Total value

Assuming that the farm operator allocates water to maximize total farm net income, including all water costs, economic values comparing the two water supply situations are shown in the tables.

3.7.2. Average value

With a high supply and low price, average farm income from surface water is $72,500 per acre for a 500 acre farm divided by 1250 acre feet, which is $58 per acre foot (Table 2, top row). So $58 per acre foot is the average value of existing farm water used at the source, which can be compared directly with municipal residential or other values of water used at the source, such as endangered species critical habitat.

Average values of existing agricultural water used per unit of use are attractive for facilitating common denominator comparisons. Nevertheless, they are misleading for policy analysis because average values look backwards, value only existing use, and are unable to evaluate plans that would augment that current use. Because average values are based only on historical use patterns, they tend to inflate the impacts of changing current use. For policies that would change current use patterns, marginal values provide more useful information.

Table 2
Economic value of water in agriculture[a]

Alternative future		Farm operator choices		Economic value of surface water								
Supply ac-ft/ac	Price $/ac-ft	Surface ac-ft/ac	Groundac-ft/ac	Total[b]			Average[c]			Marginal[d]		
				Income[e] 1000s	Bill[f] 1000s	Value[g] 1000s	Income $/ac-ft	Bill $/ac-ft	Value$/ac-ft	Income $/ac-ft	Bill $/ac-ft	Value $/ac-ft
3	18.0	2.50	0.00	72.5	22.5	95.0	58.0	18.0	76.0	0.0	18.0	18.0
3	36.0	2.50	0.00	50.0	45.0	95.0	40.0	36.0	76.0	0.0	36.0	36.0
3	54.0	2.50	0.00	27.5	67.5	95.0	22.0	54.0	76.0	0.0	54.0	54.0
3	72.0	1.25	1.25	12.5	45.0	57.5	20.0	72.0	92.0	0.0	72.0	72.0
2	18.0	2.00	0.50	62.0	18.0	80.0	62.0	18.0	80.0	42.0	18.0	60.0
2	36.0	2.00	0.50	44.0	36.0	80.0	44.0	36.0	80.0	24.0	36.0	60.0
2	54.0	2.00	0.50	26.0	54.0	80.0	26.0	54.0	80.0	6.0	54.0	60.0
2	72.0	1.25	1.25	12.5	45.0	57.5	20.0	72.0	92.0	0.0	72.0	72.0
1	18.0	1.00	1.50	37.0	9.0	46.0	74.0	18.0	92.0	74.0	18.0	92.0
1	36.0	1.00	1.50	28.0	18.0	46.0	56.0	36.0	92.0	56.0	36.0	92.0
1	54.0	1.00	1.50	19.0	27.0	46.0	38.0	54.0	92.0	38.0	54.0	92.0
1	72.0	1.00	1.50	10.0	36.0	46.0	20.0	72.0	92.0	20.0	72.0	92.0

[a] *Current conditions*: Operator farms 500 acres cotton. Cotton price = $1/lb. Groundwater pumping costs = $36/ac-ft; non-water production costs = $500/ac; surface water cost varies by alternative future. 500 total acres can be farmed, consisting of any acreage combination using the three crop-water technologies described below.

Surface water technology: Cotton uses 2.5 ac-ft/ac surface water only; Cotton yield = 750 lb/ac.

Mixed technology: Cotton uses 1.25 ac-ft/ac. surface water + 1.25 ac-ft/ac, groundwater Cotton Yield = 720 lb/ac.

Groundwater technology: Cotton uses 2.5 ac-ft/ac groundwater only. Cotton Yield = 650 lb/ac.

Alternative futures: Table shows 12 combinations of surface water price + supply. Surface water cost varies from $18 to $72/ac-ft. Surface water supply varies from 1 to 3 ac-ft/ac. *Tabled results*: Income-maximizing actions based on linear programming models for each of the above alternative futures.

[b] Total is total for the 500 acre farm for all surface water used.

[c] Average is the total divided by the total number of acre feet of surface water used for the farm.

[d] Marginal is additional amount produced by one extra acre foot of water used for the farm.

[e] Income is maximum net revenue with surface and groundwater minus maximum net income with only groundwater.

[f] Bill is total surface water bill for the farm, i.e. total price per acre foot multiplied by total acre feet used.

[g] Value is total economic value of surface water, i.e. added net income + total water bill.

3.7.3. Marginal value

Information on the marginal value of water in agriculture can be used to evaluate changes in policies that would alter current farm water supplies or water use patterns. These values enable policy analysts to look forward and examine impacts of future policy proposals. The marginal value is the added amount that would be produced if one extra acre foot per year were supplied. Marginal values per incremental unit of volume can be compared across water policy proposals, for example comparing the value of water in agriculture versus cities versus endangered species critical habitat.

Consider the example of added irrigation water supplied at a low price when supply is already high shown in Table 2, top row. The marginal net income resulting from expanding capacity from its current 3 to 4 acre feet per acre is zero. This is considerably lower than the $58 average net farm income per acre foot of existing water used. The reason for this zero marginal net income is that at the current $18 per acre foot water price, not all the supply is used. The only time that the added net farm income from additional surface water supplied exceeds zero is when the current supply is fully used. For policy analysis, this means that proposals that would expand current capacity from 1500 acre feet (3 acre feet per acre) to 1501 acre feet is less than the $18 per acre foot price of water, since the added water would have no buyers at that price.

3.8. Policy analysis

Two examples from a recent drought policy analysis of the Rio Grande Basin are shown to illustrate how the information on the economic value of water can be used for policy analysis (Ward et al., 2001).

3.8.1. Value of water lost from agriculture: endangered species

Table 3 shows impacts on agriculture of a policy that would reduce irrigation water use by the Middle Rio Grande Conservancy District (MRGCD) New Mexico by 60,000 acre feet per year to supply critical habitat for the endangered silvery minnow near Albuquerque, New Mexico. A full allocation of water to agriculture depletes the stream by 324,000 acre feet, produces $11.7 million per year, and dries the riverbed in mid summer. We assume that reducing water use by MRGCD from 324,000 to 264,000 acre feet annually produces sufficient flow for the minnow.[31] Annual farm income falls from $11.7 to $10.1 million, producing a total cost of loss of income by supplying those minnow flows of $1.6 million. The average value of water in agriculture is about $36 per acre foot consumed ($11.7 million/324,000 acre feet). The marginal value of water lost to supply the minnow flows is defined as the total loss in farm income divided by the total water taken from agriculture. It is computed as $27 per acre foot consumed, ($11.7–$10.1 million)/(324,000–264,000 acre feet), much lower than the average value.

3.8.2. Value of water lost from agriculture: drought

Table 4 shows similar impacts on El Paso, Texas irrigated agriculture of a drought that reduces water use by 30,000 acre feet per year in the Rio Grande. A normal full allocation of surface water depletes the stream by about 236,000 acre feet, which produces $26.2 million per year in net farm

[31] Actual flows required for the minnow are widely debated.

Table 3
Economic value of water lost in agriculture: endangered species

Surface water ac-ft	Kind of economic impact	Total $/year lost	Average $/ac-ft	Marginal $/ac-ft lost
−60,000	Income	1,616,332	36	27
	Bill (price = $0/ac-ft)	0	0	0
	Value	1,616,332	36	27

Policy reduces water supplied to Middle Rio Grande Conservancy District (MRGCD) farmers near Albuquerque from a normal of 324,000 acre feet per season for silvery minnow critical habitat on the Rio Grande above Elephant Butte. With a full allocation of 324,000 acre feet, total district net income is $11,720,000. With only 264,000 acre feet, total net income is $10,108,000.
ac-ft: acre foot.

Table 4
Economic value of water lost in agriculture: drought

Surface water ac-ft	Kind of economic impact	Total $/year lost	Average $/acre foot	Marginal $/ac-ft lost
−30,000	Income	2,392,969	111	80
	Bill (price = $15/ac-ft)	450,000	15	15
	Value	2,842,969	126	95

Details: Drought reduces surface water to El Paso agriculture from a normal of 236,000–206,000 acre feet per year. With a full allocation of 236,000 acre feet, total district income is $26,238,000; With only 206,000 acre feet, total income is $23,844,000.
ac-ft: acre foot.

income. Under drought conditions, stream depletion is 206,000 acre feet, producing a loss of about $23.8 million. The total loss of income due to drought is $2.4 million, which is the total value of water lost in agriculture to drought. Under a full allocation the average value of water is about $111 per acre foot consumed ($26.2 million/236,000 acre feet). The marginal value of water lost to drought is about $80 per acre foot consumed, computed as ($26.2 million–23.8 million)/(236,000 acre feet–206,000 acre feet).

4. Conclusions

Rational decisions supporting water resource development, allocation, and use require measuring the economic value of water in alternative uses. Developing a concept of value that is useful for policy analysis requires a clear statement of what the policy decision aims to achieve. The economic value of water measures the contribution of that water to accomplishing that decision's aim. When the market system works efficiently, the price of water signals an accurate measure of its economic value. There is no single economic value of water. People will pay thousands of dollars for a quart of water if it keeps them alive. When flood conditions threaten lives and property, people will pay thousands of dollars to fight floods that keep water away.

The economic value of water comes from the many uses to which water can be put in satisfying people's needs. The benefits from a particular increment of water supply in a given location in a river basin is the sum of the values produced in the first location and the value of all altered return flows in all subsequent uses, locations, and time periods. Several economic and hydrologic factors affect the value of water. These include which sector uses the water, the type of product supplied by the sector, the demand for the water's final product, the site productivity of the location where the water is used, the level of complementary resources at the site and transportation, storage, and processing costs for off-stream uses.

Translation of the physical effects of a proposed water program into economic benefits and costs involves estimating values of the increases and decreases in goods and services under future conditions *with* and *without* the program. The economic benefit of additional water used in irrigation is measured as the change in value of agricultural products less changes in associated production costs.

For purposes of economic policy analysis, benefits and costs should be measured from the same view, period of time, and program aims. Information on water's economic value enables decision makers to make more informed choices on water development, allocation, and use, in which growing demands for all uses are made in the face of increased scarcity.

References

Acharya, G. (2000). Approaches to valuing the hidden hydrological services of wetland ecosystems. *Ecological Economics*, *35*(1), 63–74.

Acharya, G., & Barbier, E. B. (2000). Valuing groundwater recharge through agricultural production in the Hadejia–Nguru Wetlands in Northern Nigeria. *Agricultural Economics*, *22*(3), 247–259.

Barbier, E. B. (2000). Valuing the environment as input: Review of applications to mangrove–fishery linkages. *Ecological Economics*, *35*(1), 47–61.

Bell, F. W. (1997). The economic valuation of saltwater marsh supporting marine recreational fishing in the southeastern United States. *Ecological Economics*, *21*(3), 243–254.

Bergstrom, J. C., & Dorfman, J. H. (1994). Commodity information and willingness-to-pay for groundwater quality protection. *Review of Agricultural Economics*, *16*(3), 413–425.

Blaney, H. F., & Criddle, W. D. (1962). Determining consumptive use and irrigation water requirements. *USDA Technical Bulletin,* 1275.

Brooke, A., Kendrick, D., & Meeraus, A. (1992). *GAMS: A user's guide*. Washington DC: GAMS Development Corporation.

California Department of Water Resources (1992). *The 1991 Drought Water Bank.* Sacramento, CA.

Choe, K. A., Whittington, D., & Lauria, D. T. (1996). The economic benefits of surface water quality improvements in developing countries: A case study of Davao, Philippines. *Land Economics*, *72*(4), 519–537.

Ciriacy-Wantrup, S. V. (1967). Water economics: relations to law and policy. In R. E. Clark (Ed.), *Waters and Water Rights: A Treatise on the Law of Waters and Allied Problems*, Vol. 1. (pp. 397–430). Indianapolis, IN: Allen Smith Company Publishers.

Costanza, R. (1999). The ecological, economic, and social importance of the oceans. *Ecological Economics*, *31*(2), 199–213.

Dinar, A., Knapp, K. C., Rhoades, J. D. (1986). Production function for cotton with dated irrigation quantities and qualities. *Water Resources Research*, 22(11), 1519–1525.

Dinar, A., Rhoades, J. D., Nash, P., & Waggoner, B. L. (1991). Production functions relating crop yield, water quality and quantity, soil salinity, and drainage volume. *Agricultural Water Management*, *19*, 51–66.

Doorenbos, J., & Pruitt,W. O. (1975). Guidelines for prediction of crop water requirements. *FAO Irrigation and Drainage Paper.* Vol. 24, (179pp). Rome, Italy: FAO.

Doorenbos, J., & Pruitt, W. O. (1977). Guidelines for predicting crop water requirements. *FAO Irrigation and Drainage Paper,* Vol. 24, (2nd ed.) (156pp) Rome, Italy: FAO.

Englin, J. (1996). Estimating the amenity value of rainfall. *Annals of Regional Science*, *30*(3), 273–283.

Fadali, E. S., & Shaw, W. D. (1998). Can Recreation Values for a Lake Constitute a Market for Banked Agricultural Water? *Contemporary Economic Policy*, *16*(4), 433–441.

Frederick, K. D., Vandenberg, T., & Hanson, J. (1996). Economic values of freshwater in the United States. Jean Publication: *Resources for the Future Discussion Paper*, 97/03.

Freeman, A. M., III. (1995). The benefits of water quality improvements for marine recreation: A review of the empirical evidence. *Marine Resource Economics*, *10*(4), 385–406 (Doc. Type: Journal Article Libraries: 73. (EconLit)).

Goodman, S. L., Seabrooke, W., & Jaffry, S. A. (1998). Considering conservation value in economic appraisals of coastal resources. *Journal of Environmental Planning and Management*, *41*(3), 313–336.

Griffin, R. C. (1998). The fundamental principles of cost-benefit analysis. *Water Resources Research*, *34*(8), 2063–2071.

Hall, D. (2000). Public choice and water rate design. In A. Dinar (Ed.), *The Political Economy of Water Pricing Implementation*. Oxford: Oxford University Press.

Howe, C. W. (1987). Project benefits and costs from national and regional viewpoints: Methodological issues and case study of the Colorado Big Thompson Project. *Natural Resources Journal*, *27*(1), 5–19.

Huppert, D. D. (1999). Snake river salmon recovery: Quantifying the costs. *Contemporary Economic Policy*, *17*(4), 476–491 (Doc. Type: Journal).

Jensen, M. E., Burman, R. D., & Allen, R. G. (1990). Evapotranspiration and irrigation water requirements. *ASCE manuals and reports on engineering practice*, Vol. 70. New York: American Society of Civil Engineers.

Kaoru, Y., Smith, Kerry, V., & Long, L. J. (1995). Using random utility models to estimate the recreational value of estuarine resources. *American Journal of Agricultural Economics*, *77*(1), 141–151.

Kosz, M. (1996). Valuing riverside wetlands: The case of the "Donau-Auen" national park. *Ecological Economics*, *16*(2), 109–127.

Lety, J., & Dinar, A. (1986). Simulated crop-water production functions for several crops when irrigated with saline waters. *Hilgardia*, *54*(1), 1–32.

Lety, J., Dinar, A., & Knapp, K. C. (1985). Crop-water production function model for saline irrigation waters. *Soil Science Society American Journal*, *49*, 1005–1009.

Marglin, S. A. (1962). Objectives of water resources development: A general statement, (Chapter 2 of Arthur Maass, et al.) *Design of water resource systems*. Cambridge: Harvard University Press.

Martin, W. E., & Young, R. A. (1967). The need for additional water in the arid southwest. An economist's dissent, university of Arizona Agricultural Experiment Station Journal Series Article 1450.

McCann, L., & Easter, W. K. (2000). Estimates of public sector transaction costs in NRCS programs. *Journal of Agricultural and Applied Economics*, *32*(3), 555–563.

McKenney, M. S., & Rosenberg, N. J. (1991). Simulating the impacts of climate change on potential evaportranspiration: A comparison of the climate sensitivity of selected methods. Resources for the Future Energy and Natural Resources Division Discussion Paper: ENR91–17.

Merrett, S. (1997). *Introduction to the economics of water resources: An international perspective*. London: University College London Press.

Molden, D., Sakthivadivel, R., & Habib, Z. (2001). *Basin-level use and productivity of water: examples from South Asia*. Research Report 49, International Water Management Institute.

Molden, D., Sakthivadivel, R., Perry, C. J., de Fraiture, C., & Kloezen, W. H. (1988). *Indicators for Comparing Performance of Irrigated Agricultural Systems*. Research Report 20, Colombo, Sri Lanka: International Water Management Institute.

Naeser, R. B., & Bennett, L. L. (1998). The cost of noncompliance: The economic value of water in the middle Arkansas River valley. *Natural Resources Journal*, *38*(3), 445–463.

Perry, C. J. (2001). Water at any price? Issues and options for charging for irrigation water. *Irrigation and Drainage*, *50*, 1–7.

Rhodes, F. M., & Bennett, J. M. (1990). Corn. In Steward, B. A., & Nielsen, D. R., (Eds.), *Irrigation of agricultural crops*, Agronomy Series No. 30. Madison, WI: American Society of Agronomy.

RiverWare (2002). http://cadswes.colorado.edu/PDF/Release Notes/EngrObjs.pdf.

Stevens, T. H., Barrett, C., & Willis, C. E. (1997). Conjoint analysis of groundwater protection programs. *Agricultural and Resource Economics Review*, *26*(2), 229–236.

Swallow, S. K. (1994). Renewable and nonrenewable resource theory applied to coastal agriculture, forest, wetland, and fishery linkages. *Marine Resource Economics*, *9*(4), 291–310 (Doc. Type: Journal Article Libraries: 73 (EconList)).

Trelease, F. J. (1965). Policies for water law: Property rights, economic forces, and public regulation. *Natural Resources Journal*, *5*(1), 1–48.

US Bureau of the Budget (1952). Reports and budget estimates relating to federal programs and projects for conservation, development and use of water and related land resources, Circular A-47, Washington.

US Congress (1962). Policies, standards and procedures in the formulation, evaluation and review of plans for use and development of water and related land resources. 87th Congress, 2nd Session, Senate Document 97.

US Interagency Committee on Water Resources (1958). *Proposed practices for economic analysis of river basin projects, revised* (The "green book"). Washington: US Government Printing Office.

US Water Resources Council (1973). Procedures for evaluation of water and related land resources projects, *Federal Register*, *38*(174), 24776–24869.

US Water Resources Council (1979). Procedures for evaluation of national economic development benefits and costs in water resources planning, Level C; Final rule; *Federal Register*, *44*(242), 72892–72976.

US Water Resources Council (1983). Economic and environmental principles and guidelines for water and related land resources implementation studies Washington: Government Printing Office.

Ward, F. A., & Beal, D. (2000). *Valuing nature with travel cost models: A manual*. Cheltenham, UK: Edward Elgar.

Ward, F. A., & King, J. P. (1998). Reducing Institutional Barriers to Water Conservation. *Water Policy*, *1*, 411–420.

Ward, F. A., Young, R. A., Lacewell, R., King, J. P., Frasier, M., McGuckin, J. T., DuMars, C., Booker, J., Ellis, J., & Srinivasan, R. (2001). Institutional adjustments for coping with prolonged and severe drought in the rio grande basin. final report to US Geological Survey.

Willis, D. B., & Whittlesey, N. K. (1998). Water management policies for streamflow augmentation in an irrigated river basin. *Journal of Agricultural and Resource Economics*, *23*(1), 170–190.

Wollman, N. (1962). *The value of water in alternative uses*. Albuquerque, NM: University of New Mexico Press.

Young, R. A., & Gray, S. L. (1972). *Economic value of water: Concepts and empirical estimates*. Department of economics, Colorado State University, Fort Collins, Colorado, Final Report to the National Water Commission, Contract NWC 70–028, March.

Young, R. A., & Haveman, R. H. (1985). Economics of water resources: a survey. In A. V. Kneese, & J. L. Sweeney (Eds.), *Handbook of Natural Resource and Energy Economics*, Vol. I (pp. 465–521). New York: North-Holland.