Concepts and Methods for Assessing Economic Impacts from Climate Change on Water Resources

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ABSTRACT

Be it on local, regional, national, or global scale, climate change alters temperature and precipitation regimes, affecting economic and environmental systems. Economic assessment of potential effects of anticipated climate change and evaluation of possible policies, planning, and adaption strategies provides insights for improved environmental and economic management. The aims of this chapter are twofold: First, provide a primer on economic concepts and principles that underlie methods of resource and environmental valuation. And second, describe hydro-economic modeling of watershed assessment to assess climate change effects and adaptation strategies.

INTRODUCTION

Climate and water are among the most important physical processes and systems affecting and afflicting human settlements and environmental systems. Highly interconnected and vital to survival, both support necessary human and environmental requirements for food and energy. Developing, improving and extending understanding of human dependence on and interdependence with these systems is essential for effective, long-run water and climate decision making and policy design. Toward this goal, this chapter is a primer on the economic concepts of economic valuation, demand and supply and benefit, followed by a discussion of the estimation of economic value, and climate change assessment approaches and including hydro-economic models.

VALUATION MEASURES, METRICS AND CONCEPTS

a. Physical Measures and Metrics

The physical phenomenon of climate and hydrologic systems have inspired corresponding physical metrics including *virtual water* and the concept of *carbon*- and *water-footprints* (respectively, Allan, 2001; Wiedmann and Minx, 2008; Hoekstra and Hung, 2002; Chapagain and Hoekstra, 2004). Water footprints, for example, account for activities such as food production and manufacturing in terms of water volumes derived from surface- and ground-water (blue water), captured rainfall or soil moisture (green water), and needed to assimilate and transport waste and by-products (grey water).

Footprints are then used in accounting frameworks to measure regional water consequences of economic development and trade (Chapagain and Hoekstra, 2004).

Water footprint accounting avoids complications of money-denominated metrics, difficulties with inter-personal and inter-country comparisons, distributional equality, and distortions from valuing (or not) non-market effects. However, water footprints (and other physical-based accounting metrics) suffer similarly from shortcomings of consistency, comparability and subjectivity (Wilchens, 2011 and Merrett, 2003). Furthermore, by effectively transforming water into a value-metric, or currency, the approach masks differences in water's relative economic performance and contribution, for example, equating water content of low- and high-valued products. Just as Marx's labor theory of value was rejected, a ton steel cannot be valued by labor inputs, nor can a pound of beef be valued by virtual water input.

In contrast to the physical metrics, economics' usefulness in climate change and water resource accounting and decision frameworks has four dimensions:

First, economic models account for the transformation of water, climate, land, labor and capital into manufactured assets, durable and consumer goods by assigning each a 'shadow' value (price), which measures and weights each input's relative economic contribution. Unpriced inputs -- or input prices that fail to reflect relative scarcity – are a sign of market failure.

Second, the flow and exchange of goods and services, money and income, and accumulation of wealth and knowledge are measured.

Third, human behavior, motivations (i.e., incentives, goals and constraints) and social interactions (i.e., collective action and governance) can be understood, organized and modeled.

Fourth, decisions can be made through metrics and approaches that sort, weight, evaluate and optimize across alternative activities, investments and choices.

b. Economic Perspectives, Measures and Metrics

Value, utility and worth express individual wants, needs and desires, and underpin the core concepts of net benefit and opportunity cost, and demand and supply (Hanemann, 2006). They give rise also to criteria and measures that express and compare individual and societal wellbeing that are useful to guide choices and lend favor of one decision over another (Samuelson, 1947). In justifying the social expense of a bridge, French engineer Jules Dupuit (1844) first articulated the notion of *consumer surplus* which he termed 'relative utility.' This is the idea that an object's value or worth must exceed (or be no less than) the value afforded to efforts and resources relinquished in its acquisition. Dupuit recognized that price cannot be the measure of utility (value), for if it was then merely raising the price (or imposing a tariff) would in effect, raise an object's utility. In citing Smith (1776) he recognized that price reflects an object's *value-in-exchange* and is distinct from its *value-in-use* – the measure of value that counted most in Smith's eye. Marshall (1890) defined the now ubiquitous demand and supply graphs, relabeled Dupuit's 'relative utility' as consumer surplus, and introduced producer surplus (excess of revenue over variable costs). Although non-economists sometimes confuse, misinterpret and conflate price, cost and value, as Hanemann (2006) describes:

'EXTRACT'

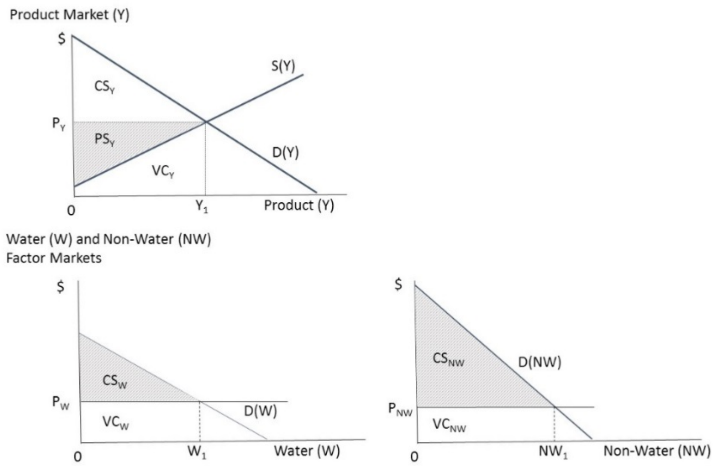
> First, demand is separate from supply. Demand indicates what things are worth to people; supply indicates what things cost. Second, market price reflects the interaction of both demand and supply and, in principle, is separate from each of them. Third, the value that people place on an item (their demand for the item) inevitably reflects their subjective preferences. (p. 63, *The Economic Conception of Water*).

Conceptually, consumer surplus retains roots in notions of cardinal utility – i.e., utility that is observable, measurable and comparable. Uncomfortable with such underpinnings, economists such as Samuelson (1947) and Hicks (1943, 1956) sought solid theoretical foundations for defining value, which they discovered could be found in the economic concepts of *indifference* and *opportunity cost*. Hicksian measures of value are grounded in two notions; first, that individuals possess the capacity to recognize, understand and compare their wellbeing across different states or conditions (i.e., based on ordinal utility and answering the question "am I better off with 'A' or with 'B'?"). And second, that individuals can use a money-metric to express the strength of desire for or aversion to a change affecting their utility. For example, expressing either the maximum amount of money they are willing-to-pay (WTP) to attain a desired object or state; or 2) the least amount they are willing-to-accept (WTA) to retain a desired object or state (Freeman, 2003). In comparing Hicksian and consumer surplus value measures, economists Willig (1976) and Morey (1984) showed that the latter, in spite of theoretical shortcomings, could be used in most applied contexts without reservation.

Marshall's demand and supply and Dupuit's surplus concepts are tied together in Figure 1 where one-output (Y) is produced with two inputs, water (W) and a composite of all non-water inputs (NW). The product market (upper panel) identifies total variable costs (VC_Y), consumer surplus (CS_Y) and producer surplus (PS_Y), and the market equilibrium that is established at price P_Y and quantity Y_1 for consumer demand D(Y) and industry supply S(Y). The two lower panels show markets for water and non-water inputs, respectively, and within each, areas identify consumer surplus (CS_W and CS_{NW}) and total factor payments (VC_W and VC_{NW}) associated with input prices (P_W and P_{NW}) and optimized inputs (W_1 and NW_1). Producer surplus in the product market (PS_Y) equals the sum of consumer surplus (CS_W and CS_{NW}) across all factor markets (Just, Hueth and Schmitz, 2004). Similarly, the area under product supply is total variable cost (VC_Y) and equals the sum of variable factor payments (VC_W and VC_{NW}). The *net benefit* of water – is the consumer surplus in the water market (CS_W), and is equivalent to producer surplus (PS_Y) in the product market less non-water net benefits (CS_{NW}).

<FIGURE 1 ABOUT HERE>

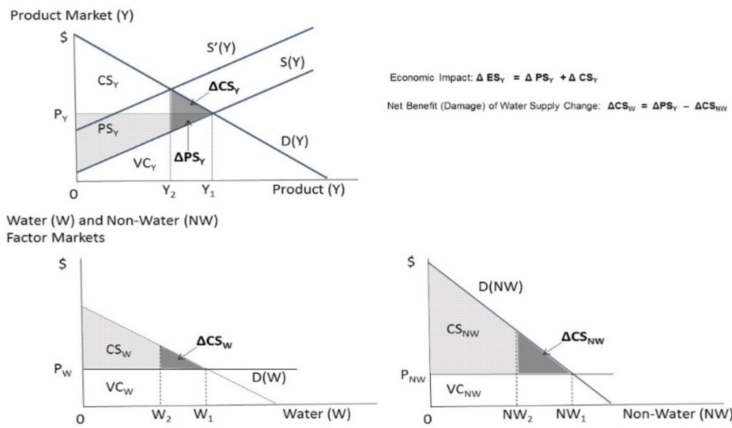
Figure 1. Valuing Water in Product and Factor Markets



Using Figure 1 as the baseline, the economic damages to agriculture (i.e., cost-benefit analysis) of a drought is illustrated in Figure 2. Assuming no available economically-viable alternatives, drought reduces water use from W_1 to W_2 and non-water inputs from NW_1 to NW_2. Drought damages are given by the consumer surplus change ΔCS_W defined under the water demand D(W). In the short-run only variable non-water inputs are reduced; however, in the longer-run many – but not necessarily all -- non-water fixed and durable assets and capital will be re-employed.

<Figure 2 ABOUT HERE>

Figure 2. Estimating Economic Damages from Water Supply Changes: Net Benefits, Economic Impacts and the Value of Water in Product and Factor Markets



Reduced inputs cause output to fall, as shown by a shift in product supply to S'(Y). For the region and sector, the *economic impact* or loss flowing from reduced water supplies is measured by summing the net changes in consumer and producer surplus (ΔCS_Y and ΔPS_Y). However, these economic impacts result not only from reduced water supplies, but importantly, also from reduced use of non-water inputs – inputs with other opportunities to be used or employed. Therefore, if concern is on the role and value of water, its economic contribution to the region and sector, and its share of damages when reduced, then the principle measure of interest is change in water's *net benefit,* CS_W. Hamilton et al., (1991) highlight the differences between *economic impacts* and *net benefits*, which they summarize as, "net benefits equal impacts less opportunity costs." Therefore, water's contribution to damages when supplies are reduced -- or conversely to gains when supplies are increased -- is limited to its share of *economic impact,* shown as the ratio of $CS_W/(PS_Y + CS_Y)$. Furthermore, in judging the efficacy of any long-run adaptations, such as a dam to increase water storage capacity, overall project costs are properly compared to avoided-losses-in-net-benefits (CS_W), and not to avoided-losses-in-economic-impacts. In a cost-benefit-analysis (CBA), for example, using the latter would overstate project benefits, which could increase the likelihood the project is undertaken and the likelihood that desired outcomes are realized (Booker et al., 2012; Hamilton et al., 1991, 1989; Griffin 1995, 1998, 2006; Young and Haveman, 1985; Young, 2005).

VALUING WATER

Whether motivated by 1) the desire to maximize utility and wellbeing from goods, services and experiences by using resources efficiently and optimally (economist perspective), or 2) the desire to minimize disutility from regretful mistakes and adverse outcomes resulting from resource misuse and maladaptation (environmentalist perspective), good knowledge and information is fundamental. This human capital is developed, accumulated, adapted and revised through experience and observation concerning i) physical conditions and relationships, ii) resource availability (scarcity) and substitutability, and iii) technical possibilities for resource transformation. With so many moving parts how can all this information be condensed and distilled into useable forms for decision making?

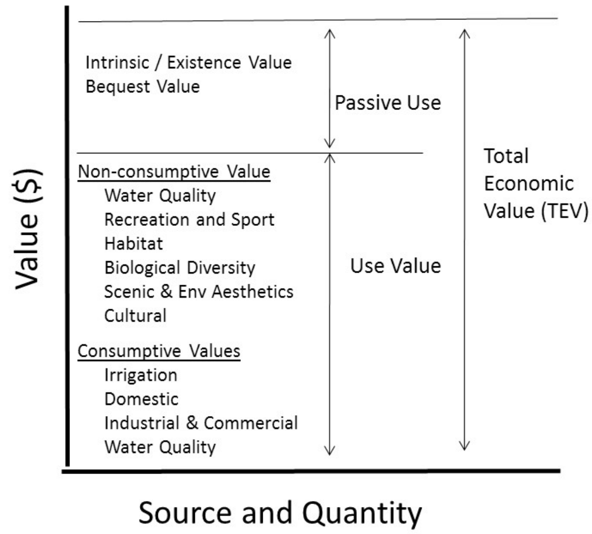
Described earlier (i.e., ‘dimension one’), economics helps give measure to resource scarcity and substitutability through prices. Prices signal scarcity, value and opportunity cost, without such signals (weights) neither solution to the motivation problems above is possible. Missing or drastically incorrect prices misrepresent actual resource value (opportunity cost). For example, low or missing prices imply absence of scarcity (i.e., abundance). It seems, therefore, rather incongruous, inconsistent and contradictory that many water institutions and policies – in arid regions no less -- act deliberately to leave water effectively unpriced.

Markets can be useful sources of price information, and are useful and necessary starting points for data collection. However, market price data are often influenced by many factors, aside from relative scarcity and use, which possibly distort, bias or limit their use to highly specific conditions. In addition, many resources are unpriced in markets. If the supply of these non-market resources (e.g., water, land and air) is limited, scarce or subject to significant degradation (e.g., pollution and overuse), then consideration and valuation is important to their efficient and effective management (Freeman, 2003; Loomis, 2000).

To broaden consideration of water's value to non-market resources consider the multiple perspectives listed in Figure 3, showing a taxonomy of value types. Broadly categorized into 'passive' and 'active' use, water services encompass a wide and diverse range over which people experience and derive utility. Active use is further characterized as 'consumptive' and 'non-consumptive.' The concept of 'total-economic-value' (TEV) is expressed as summing over all values (Loomis, 2000; Rogers et al., 1998).

<FIGURE 3 ABOUT HERE>

Figure 3. Total Economic Value of Water: Sources, Types and Uses



Source: Derived from Rogers, Bhatia, Huber (1998). **Water as a Social and Economic Good: How to Put the Principal into Practice**.
http://info.worldbank.org/etools/docs/library/80637/IWRM4_TEC02-WaterAsSocialEconGood-Rogers.pdf

For practitioners, judgment must be used to recognize the relative and potential magnitude of these value sources, to indicate some measure of the relative importance for pursuing measurement, and to illuminate the plausible bias from its omission. For example, recognize that benefit estimates based solely on market prices and quantities are clearly lower-bound estimates of consumer surplus. Loomis (2000) discusses techniques and approaches for developing and using estimated economic values of environmental uses and services from water resources. In some cases, water planning manuals specify and standardize approaches for non-market economic and environmental valuations, for example, the Organization for Economic Cooperation and Development, *Management of Water Projects* (OECD, 1985), and the *Practices and Guidelines* given by the U.S. Water Resources Council (1983) for federal projects (and currently in revision).

a. Valuing Water in Competing and Non-Competing Uses

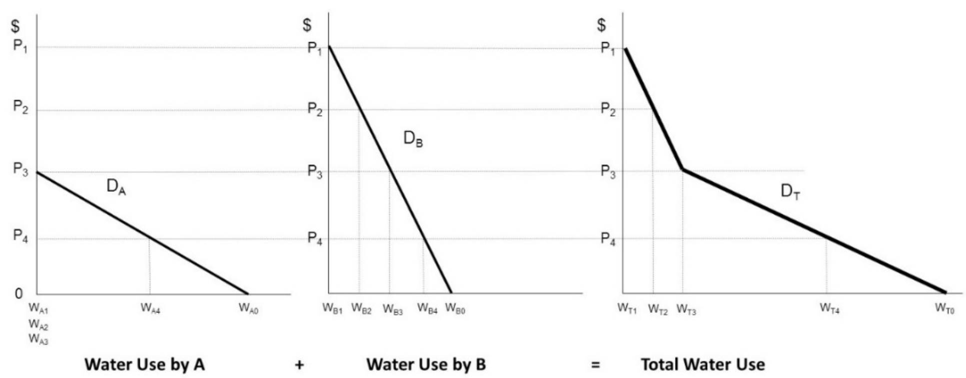
With so many varied uses, services and pathways to consider it is not surprising that economic valuation of water is not a simple task, e.g., one where market prices are adequate value indicators. In fact, in most settings where climate changes are concerned markets are very incomplete sources for information on water's value. Markets fail to ensure efficiency in water supply and use for a variety of reasons including interconnectedness (i.e., externalities), jointly enjoyed services (i.e., public goods and common pool resources), single-source water provision (i.e., natural monopoly), and high transactions costs.

Water's role is instrumental -- if not essential -- in the function and performance of so many widely varying economic and environmental systems. Perhaps more than any other resource, water is found in a wide variety of economic and environmental goods and services. Some uses result in significant physical transformations thus altering the disposition and subsequent use of water such that it can be considered consumed, for example, evapotranspiration in crop production. Other uses may redirect or temporarily displace water from its natural course but otherwise leaving it substantially unaffected, for example, in hydropower production or instream recreation. Water can be used and valued for its ability to assimilate and transport waste and by-products, perhaps altering its physical chemistry but not its volume. These distinctions may have bearing on the approach to valuation, for example, differences in approaches for valuing *consumptive-* and *non-consumptive-use*.

Consumptive-uses are most familiar and typically involve diverting waters from lakes and streams and applying them to specific productive uses such as irrigation, municipal and industrial, and thermo-electric power generation. Such uses are competitive and economists use the term *rival*, use reduces the amount available to other users. Aggregating demands across all potential users (buyers) to estimate benefits and illustrate the aggregate demand curve follows the process of adding-up all the individual quantities demanded for each and every price (i.e., *horizontal summation* of demands). This concept is illustrated in Figure 4.

<FIGURE 4 ABOUT HERE>

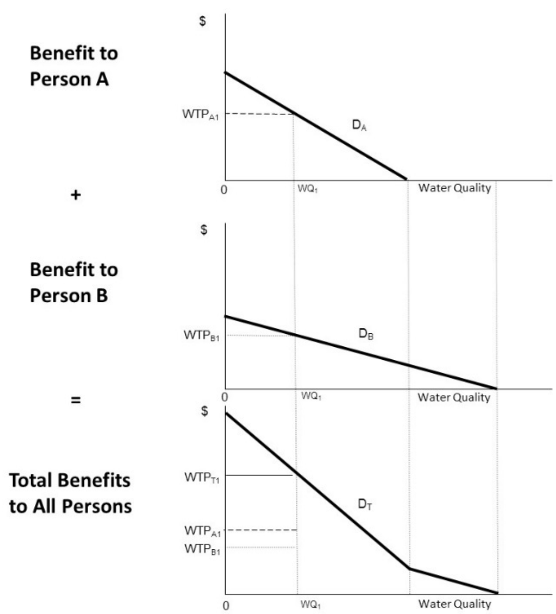
Figure 4. Horizontal Summation of Rivalrous Demands



By comparison, non-consumptive-uses, including those that are passive-use, do not subtract from the available water or capacity for enjoyment of water services by others. For example, efforts to reduce total-dissolved-solids (TDS) levels by 500 ppm in a seriously impaired river would measurably improve water quality. Although each user's value (i.e., willingness-to-pay) for such improvement likely differs, the benefits are equally available to all -- including the aquatic environment -- and should be included in the benefit assessment. To illustrate aggregate demand and estimate benefits for non-rivalrous goods and services, each affected individual's WTP for the given change are summed (i.e., *vertical summation*). This concept is illustrated in Figure 5.

<FIGURE 5 ABOUT HERE >

Figure 5. Vertical Summation of Non-Rivalrous Demands



In addition to the characteristic of non-rivalry, if the good or service also possesses characteristics that make it very costly -- or virtually impossible -- to exclude non-paying individuals from enjoying its benefits, then economists would classify this as a *public good.* A related case is where consumption is rival but costs of excluding others from taking advantage are high, either because property rights or rules are undefined or enforcement is low. In describing why open access to grazing lands results in resource degradation, i.e., conditions where access to valuable resources is unrestricted, Hardin (1968) coined the phrase *tragedy-of-the-commons*, and which economist's use terms open-access or common-pool resources. These conditions are often a challenge for efficient resource management including open-ocean fisheries, regional and trans-national aquifers, and water quality protection (Ostrum, 1990).

These are considered cases of *market failure*, because physical characteristics prevent individuals, freely-acting to serve their own best interest (i.e., *the market*), from attaining the maximum net benefit. For example, with public goods the presence of free-riders (i.e., those who enjoy the private benefit but try to avoid bearing the cost) results in too little of good produced (e.g., water quality). Similarly, common-pool resources are characterized by conditions that encourage excessive and exploitive efforts often resulting in severe resource degradation, exhaustion and collapse. To enhance economic welfare, some type of corrective action is needed that generates cooperation across the affected parties e.g., through formation of cooperative or collective actions and governance, including rules, regulations and policies and their enforcement (Ostrum, 1990).

b. The Importance of Externalities in Assessing Water Resources

Markets also fail when incorrect prices distort and misdirect efforts and resource use. Especially true when water, food and energy policies, for example, mask and decouple water's scarcity value from its price – either through direct market interventions or deliberate policy e.g., providing citizens with 'cheap food' and 'cheap water.' If distortions leading to under-valued water were reduced or limited then so would be the push and need for alternative metrics, such as virtual water.

Markets fail too when individual actions and activities have unpriced, unintended and unconsidered effects on others, often because of the physical characteristics of the resource or system. Examples are numerous and include upstream activities that diminish or degrade downstream water supplies, and actions that change return flow patterns that recharge aquifers (e.g., lining canals and installation of drip-irrigation). These so-called third-party effects are given the term *externalities* (Meade, 1973). Externalities are common in highly-interrelated hydrologic systems, such as watersheds, where actions, decisions and behaviors of some water users affect water conditions facing other users.

Externalities can be positive or negative, spatially and temporally complex, and may be reciprocal (e.g., an individual who simultaneously generates and receives external effects). Water transfers, in general, fail to account for any positive externalities (Hartman and Seastone, 1970). Taylor et al., (2014) examine the policy implications of reciprocal externalities for conjunctive surface-ground-water systems, where ground-water pumpers near a canal enjoy the positive externality of canal seepage while inflicting a negative externality of pumping-induced seepage upon the canal user. The market failure is that the amount of water diverted into a leaky canal is under-produced while the amount of pumping from a well that is hydrologically connected to the canal is over-produced. Consider the case of two irrigators using water from a river, one pumps from a riparian aquifer and the other diverts from the river. When determining pumping and diversion rates, respectively, they ignore any effects each has on the other’s water supply. For example, with greater diversions the surface irrigator may have positive effects on recharging the pumper's aquifer, or alternatively may experience a loss of diversion capacity as pumping rates increase. In this case, the nature of the externality depends on relative position in the system. In either case, economic efficiency is not likely to attain without some intervention that stimulates cooperation and coordination across users.

c. Valuing Water as a Production Input: the Derived Demand for Water

Agriculture consumes (transforms) about 70% of the freshwater used each year, therefore it is essential that economic assessment value water as a productive factor (Young, 2005, Booker et al, 2012). In agriculture, the value of water is a derived demand in the production and marketing of crops or livestock and measures a farmer's willingness-to-pay (WTP) for water. Whether farm or firm, producers interact in both factor (input) and product markets, in the former as a buyer (consumer), in the latter as a seller (producer). Various changes and shocks affect these markets altering prices, production and producer income, including technology, policy, climate change and drought, the latter causing, for example, changes in water supply.

Consider an industry that uses water W and a vector of non-water inputs **X** to produce a single output Y. Three market relationships are external (exogenous) to the firm, demand of final product D_Y, water supply S_W, and non-water supply $S_{\mathbf{X}}$, shown as solid curves in Figure 6. Firms develop three endogenous responses, water demand D_W, non-water demand $D_{\mathbf{X}}$, and output supply S_Y, shown as dotted curves in Figure 6. The top panel depicts both the product market Y and the market for non-water inputs **X**. The product supply is the vertical sum of the two input supplies, S_W in the lower panel and $S_{\mathbf{X}}$ in the top panel. Product supply and demand intersect at the market equilibrium price P_Y and quantity Y_1, and determining required water inputs W_1 and non-water inputs $\mathbf{X_1}$. The lower panel depicts the water market with water demand D_W, derived from the difference between product demand D_Y, and non-water supply $S_{\mathbf{X}}$. At the margin, the maximum the firm can pay (WTP) for water is the difference between price and marginal cost of non-water inputs. The value of water is defined as the consumer surplus given by water demand D_W and water supply S_W, which at the margin equals its price P_W (Gardner, 1987; Floyd, 1965; Muth, 1965).

<FIGURE 6 ABOUT HERE>

Figure 6. Illustrating the Derived Demand for Water

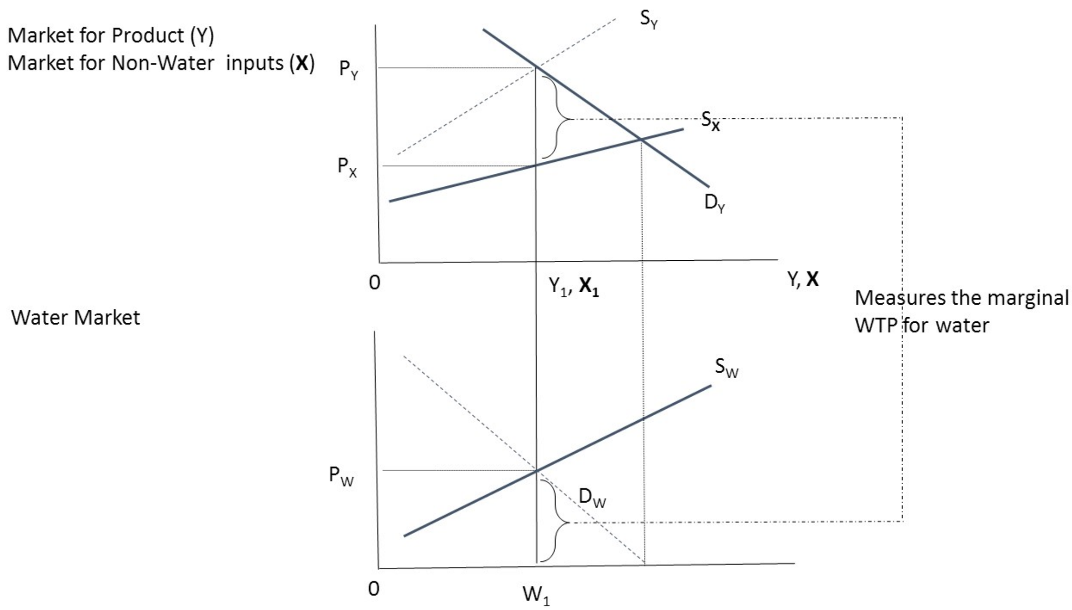


Figure is a characterization based on Gardner, 1987, Figure 4.2, p. 90 under the assumption that fixed proportions of inputs W and **X** are required to produce output Y.

All prices are in terms of dollars per unit of output (Y).

Mathematically, the demand for agricultural water is derived from the production of crop Y from water W and non-water inputs **X**:

(1) $$Y = Y(\mathbf{X}, W),$$

where **X** represents a vector of j non-water inputs (i.e., X_j) including both variable inputs such as materials (M) and labor (H), and fixed assets such as land (L) and capital (K).

Firm welfare is well-expressed by the concept of *producer surplus* (i.e., the area contained between product price and supply) that measures a firm's willingness-to-accept payment in exchange for a given quantity of product – at least enough to cover total variable costs of production. Producer's surplus is measured by a firm's long-run profit -- or by its short-run equivalent -- net returns *plus* total fixed costs, e.g., payments based on the opportunity costs of all firm-owned assets and resources including land, capital and management. Firm welfare is given by the long-run profit function Π (·):

(2) $$\prod(P_Y, P_X, P_W, \mathbf{X}, W) = P_Y \cdot Y(\mathbf{X}, W) - P_X \cdot \mathbf{X} - P_W \cdot W$$

where vector notion (**X**) applies to all inputs j, both variable and fixed. The conditions that solve for the firm's non-water and water input demands are respectively given by:

(3a) $$\frac{\delta \prod(\cdot)}{\delta X_j} = \frac{P_Y \delta Y(X_j, W)}{\delta X_j} = VMP_j = P_{X_j}$$ for each non-water variable input j

(3b) $$\frac{\delta \prod(\cdot)}{\delta W} = \frac{P_Y \delta Y(\mathbf{X}, W)}{\delta W} = VMP_W = P_W$$ for water as a variable input

where the marginal physical product (MPP) for non-water and water inputs is expressed as $\delta Y/\delta X_j$ and $\delta Y/\delta W$, respectively. The entire expression, incorporating the price of the output (P_Y), defines an input's value-of-marginal-product (VMP) and is the firm's input demand function (at least in-so-far as the partial-equilibrium context permits in which all other factors and prices are held constant). For example, water demand is shown as D(W) in Figure 1 and value as consumer surplus CS_W.

d. Methods to Measure and Value Water Productivity

Production function data from agronomic experiments and plots (e.g., Hexem and Heady, 1978) have been generally replaced by theoretical agronomic response functions in developing estimates of crop-water productivity (e.g., Martin et al., 1989; Sheieriling et al., 1997). Young (2005) and Booker et al., (2012) list seven alternative, indirect approaches to value water:

1. **Residual method** (e.g., calculated by net returns after non-water inputs are deducted, applicable where water quantity is continuously variable)
2. **Change-in-net-rents approach** (e.g., as above, except applicable where water quantity is fixed by right, lease or allotment)
3. **Mathematical programming models** (e.g., approach used in hydro-economic models, applicable for broader assessment involving many users, water sources)
4. **Alternative-cost method** (e.g., uses estimates from water supply costs as a proxy and lower-bound estimate of value)
5. **Benefit-transfer methods** (e.g., uses value estimates from secondary sources such as published papers and reports as proxy)
6. **Value-added approach** (e.g., input-output models and regional planning models such as IMPLAN® and REMI®)
7. **Average-value-product method** (e.g., a highly simplified budget analysis in which cash receipts, gross revenues or gross product are broadly and wholly attributed to water use)

The first four are most preferable and capable of producing reasonable and unbiased estimates; whereas, the latter three are technically problematic, inherently inaccurate and most likely to result in biased and inflated estimates. Young describes and cites several instances where ill-considered use of these approaches, the latter two in particular, can affect (and have affected) water policy and project assessments adversely.

The key concept underpinning the first three indirect approaches is that of *residual claimant*. The farmer's willingness-to-pay (WTP) for an input (either variable or fixed) is the amount of total revenue that remains having paid and/or valued all OTHER factors (e.g., non-water inputs). A farm, for example, produces and sells a product, earning revenue which, if the enterprise is to remain economically viable, must satisfy the costs and economic claims on that revenue by all essential, non-water inputs. The residual value is then attributed to water, expressed either as a unit price (e.g., \$ per acre-foot or \$ per cubic-meter) or total lease payment for a given water quantity, which provides an estimate of a single point on the water demand function (Young, 2005).

Accuracy of the residual approach is tied to the valuation of all *non-water* inputs. With fertilizer, seed, and hired labor, for example, there is available market price data with which to calculate value. In contrast, values for inputs such as management, risk, and family labor have to be imputed and omission or under valuing these inputs inflates the residual value of water.

The essence of the residual approach is conveyed by equations 4 and 5, where if all inputs are paid according to their VMP, then the total product value is completely allocated as:

$$(4) \qquad (P_Y \cdot Y) = (VMP_M \cdot X_M) + (VMP_H \cdot X_H) + (VMP_K \cdot X_K) + (VMP_L \cdot X_L) + (VMP_W \cdot W)$$

In choosing input quantities, profit-maximizing firms select the quantity that equates the input's price with its own value-of-marginal-product (i.e., $P_j = VMP_j$, the point at which the firm's marginal input cost equals the marginal revenue). Rearranging terms, the value-of-water can be expressed equivalently either by equation (5a) in terms of a fixed payment for a given amount (e.g., leasing a water allotment), or (5b) in terms of its imputed (shadow) price per unit (Young, 2005).

(5a) $$P_W^* \cdot W = (P_Y \cdot Y) - [(P_M \cdot X_M) + (P_H \cdot X_H) + (P_K \cdot X_K) + (P_L \cdot X_L)]$$

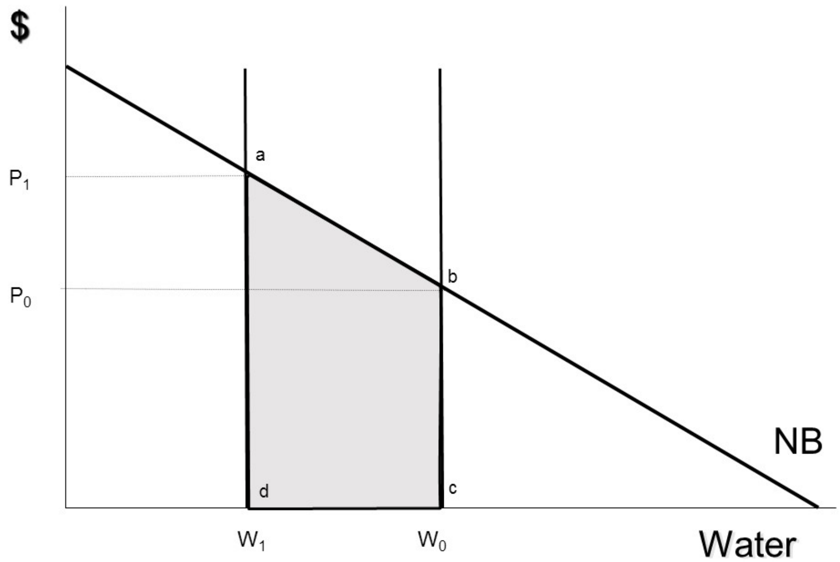
(5b) $$P_W^* = \frac{(P_Y \cdot Y) - [(P_M \cdot X_M) + (P_H \cdot X_H) + (P_K \cdot X_K) + (P_L \cdot X_L)]}{W}$$

e. A Two-Sector Model of a Hydro-Economy and the Economic Effects of Drought.

The capacity of hydro-economic models to capture and account for complexity and various changes in markets can be simplified in the concept of economic net benefit (NB) or net demand. Figure 7 shows the net demand (net benefit) function, which is derived by subtracting the supply curve from the demand curve. The economic effect of a drought is shown as the change in consumer surplus, area abcd, as available water drops from W_0 to W_1.

<FIGURE 7 ABOUT HERE>

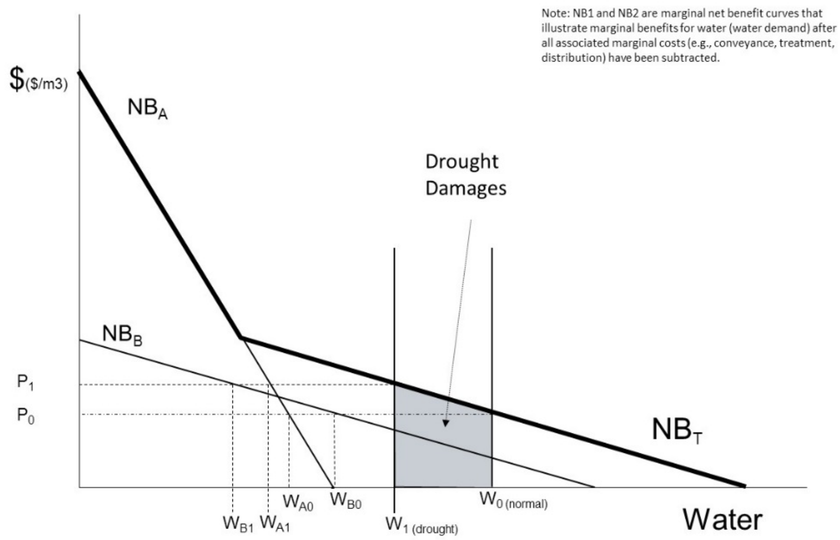
Figure 7. Net Benefits and Drought Damages in a Single-Sector Market



A two-sector model yields insight into the efficiency of market-based water allocations and policies, and hints at the mechanics underlying hydro-economic models that generalize these insights. Consider the water market shown in Figure 8 where two water users, A (city) and B (farms), compete for available water W. For A, net demand NB_A is relatively high and inelastic; and for B, net demand NB_B is relatively low and elastic. Each user's net demand is summed horizontally into total net demand, NB_T.

<FIGURE 8 ABOUT HERE>

Figure 8. A Two-Sector Model of Efficient Water Distribution, Use and Drought Damages



The water manager's initial problem is to optimally and efficiently divide and allocate available water W_0 to the users. Optimality requires that net benefits are equalized across users (i.e., equi-marginal principle). By comparing water supply W_0 to total net demand, NB_T, the marginal (scarcity) value of water is determined to be P_0. The initial (or baseline) efficient allocation is given by W_{A0} and W_{B0} for sectors A and B, respectively. Consider that a drought limits available water to W_1 and the manager must now change allocations to distribute the drought's burden fairly but economically across the two users. With W_1, water's marginal (scarcity) value rises to P_1, and new, drought-affected allocations are given by W_{A1} and W_{B1}, respectively.

Economic damages from the drought are shown in the shaded area and measured by the surplus change given by the area below net demand and change in available water. The drought burden is optimally and efficiently shared, with total damages minimized and with both users bearing some reduction in water use. User A reduces water use by the difference, W_{A0}-W_{A1}, and for user B the change is W_{B0}-W_{B1}. Differences in allocated changes in water-use can be significant across users, either on an absolute or percentage basis, and are determined by differences in demand-price elasticity. In this case, and facing P1 as the price of water, user B curtails a larger share of its use than user A. A clear result is that unless demand-price elasticities are roughly equal, though possibly perceived as 'more fair,' drought rules requiring uniform reductions in water use are not efficient, and probably are no less costly to publicize and implement than well-enforced reductions (i.e., in contrast to the relative ease of public pronouncements 'encouraging water savings' but without possibility of enforcement).

There are two key insights that summarize the results from this economic framework: 1) simple drought-sharing rules across widely varying sectors are not efficient and result in larger economic damages than necessary; and 2) with an efficient drought mitigation strategy a drought's economic burden will fall disproportionately higher on some sectors than others where valuations differ widely, although when measured *at the margin*, each sector's damage (pain) is in fact equal and as low as possible for all sectors together.

f. Important Considerations in Water Valuations and Assessments

Several characteristics and conditions can complicate proper measurement and assessment of water resources and services (Young, 2005):

1. *Well defined planning horizon, e.g., long-run or short-run.* Important to distinguish fixed and variable factors. Opportunity costs for fixed factors are

low in short-runs like drought, but higher over longer runs when opportunities exist for fixed factors to vary and move, e.g., adapting to climate change.

2. *Water input measurement, e.g., 1) variable or fixed, and 2) water diverted, water applied or water consumed.* Valuation concepts distinguish water as a fixed input – rental rates, and as a variable input -- value-of-marginal product (VMP). In addition, how water use is measured is important for understanding and assessing water-use efficiency (Lankford, 2012).
3. *Comparable water values, e.g., at-site or at-source.* Watershed scale assessment use *at-source* values, e.g., subtract delivery and treatment costs from *at-site* values.
4. *Character of market price data, e.g., extent of any omission, bias or market distortion.* Available price and wage data may not adequately or completely reflect the prevailing opportunity costs of capital and labor, including human capital, discount rates, and effects of various taxes and subsidies.

HYDRO-ECONOMIC MODELS AND METHODS FOR ASSESSING THE EFFECTS OF CLIMATE-CHANGE

Highly complex and multidimensional, comprising both physical and human interactions, the study of climate and water systems requires suitable methods (Nordhaus, 1994; Mendelsohn, 2001; Mendelsohn and Neumann, 1999, Tol, 2009). The approach of hydro-economic modeling -- based on mathematical programming methods – is a preferred approach that integrates physical, economic and institutional elements within a normative framework e.g., where objectives are defined and behavioral choices modeled and optimized (Young, 2005: Harou et al., 2009; Harou et al., 2010; Taylor et al., 2014).

a. Watershed Assessment using Hydro-Economic Modeling

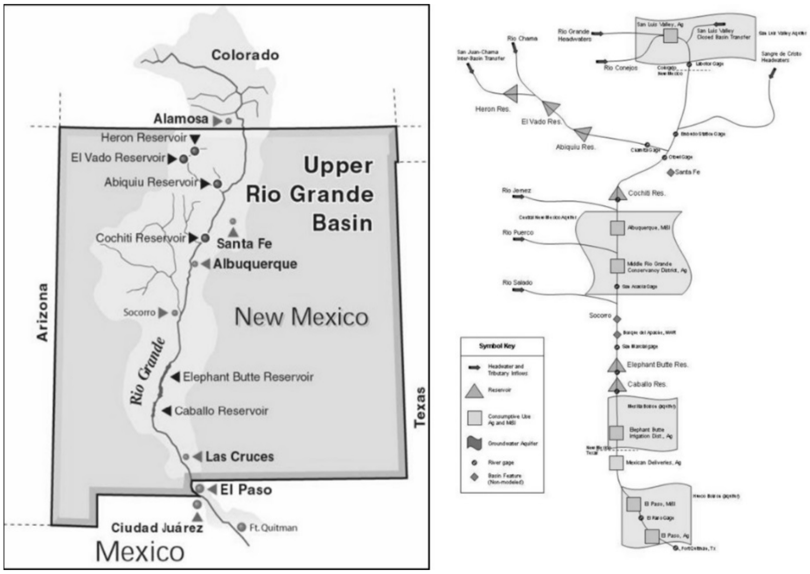
Hydro-economic models are rooted in both network models (nodes defining sources and uses and connections in between, Masss et al., 1962) and spatial equilibrium models (optimize interregional trade, Takayama and Judge 1964, 1971; Flinn and Guise, 1970; Howe and Easter, 1972; Cummings, 1974). Vaux and Howitt (1984) used these ideas to model the problem of inter-basin water transfers in California as one of maximizing producer and consumer surplus subject to water supply and distribution constraints. Booker and Young (1991, 1994; Booker 1995) took the approach to the Colorado River system, and extended it with added elements and spatial complexity, including water quality, hydropower. Hurd et al. (1999, 2001 and 2004) used Booker and Young's Colorado River Model and developed others to assess climate change impacts. Ward et al. (2001) developed a hydro-economic model to examine drought issues in the upper Rio Grande, and which has been used to assess impacts of climate change (Hurd and Coonrod, 2012) and endangered species Ward et al. (2008). For long-term planning and assessment compared to simulation and water budget models, hydro-economic models excel in their capacity to optimize water use and storage decisions and to evaluate adaptation opportunities and strategies, including those that improve water-use efficiency, policies and institutions, and infrastructure investments (Pulido-Velazquez et al., 2006; Hurd and Coonrod, 2012).

The modeling process begins by identifying a watershed and developing a conceptual (schematic) diagram of various features of the watershed including inflows, tributaries, reservoirs, aquifers, and water users. An example map and corresponding diagram developed for upper Rio Grande hydro-economic model is illustrated in Figure 9 (Ward et al., 2001; Hurd and Coonrod, 2012). The process continues by specifying model elements (e.g., objective function and constraints) and developing data and information on regarding these elements (e.g., streamflow characteristics, water demand parameters and values, reservoir characteristics).

Objective Function. The objective function defines how water generates value in the watershed, including net benefits from diversions (e.g., domestic and irrigation), reservoir storage, hydropower, wastewater assimilation, navigation, flood control, and from environmental services. Available water flowing into the basin and out from various storages is managed to maximize the *present-value-of-net-economic-benefits* (PVNB), subject to all pertinent physical, economic, and institutional constraints (e.g., network flow-balance, reservoir and aquifer storage, basin inflows and exports, policies, treaties and compacts). For consumptive uses (e.g., agriculture, municipal and industrial, and thermoelectric energy) value functions are often derived from linear demand curves and, therefore, modeled as quadratic functions of water diverted, applied or consumed. For non-consumptive uses (e.g., hydropower, instream flow for aquatic habitat, water quality, and navigation, flood control) value functions are driven by streamflow or reservoir level.

<FIGURE 9 ABOUT HERE>

Figure 9. Example of the Rio Grande Hydro-Economic Model Schematic Diagram



Equation (6) defines an example objective function across each of t time periods, n river nodes, and i consumptive uses. The objective is to choose flows F_{nt}, diversions W_{int}, aquifer pumping rates and net reservoir releases R_{nt} that maximize the discounted flow of net benefits.

$$(6)\quad PVNB = \sum_t d_t \cdot \sum_n \left(\sum_i \left[B_{nit}(W_{nit}) - C_{nit}(W_{nit}) \right] + Q_{nt}(S_{nt}) + H_{nt}(R_{nt}) + E_{nt}(F_{nt}) - D_{nt}(F_{nt}) \right),$$

where functions B_{int} and C_{nit} define benefits and costs as a function of diverted water W_{nit}, functions Q_{nt} and H_{nt} generate value from water stored S_{nt} and released R_{nt}, and functions for environmental services E_{nt} and flood damages D_{nt} are functions of flow F_{nt}.

To the extent possible, watershed-specific data and information define the form and specification of value functions. For example, quadratic net-benefit functions estimated for agriculture (A) and municipal and industrial (M&I) in the upper Rio Grande by Ward et al. (2001) and Hurd and Coonrod (2012) are shown in Figures 10 and 11, respectively.

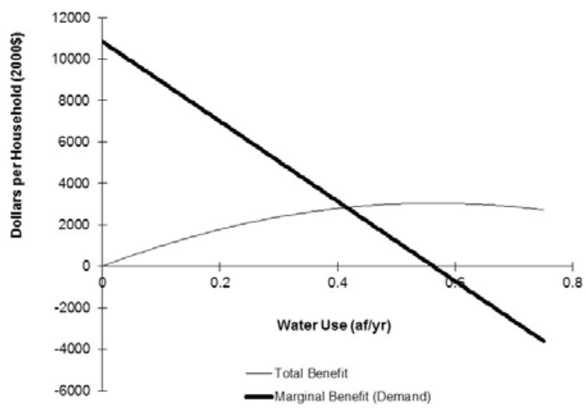
Flow Balance Constraint. A flow-balance (network) constraint models the contemporaneous flow, storage and distribution of water. It assures conformity of the model with the physical network connecting tributary inflows to main-stem river nodes, gaining and losing river reaches, return-flows and flows into and out-of reservoirs, and diversions to consumptive users. An example of which is given in Equation (7):

(7) $$F_{nt} = F_{n-1,t} + I_{nt} + R_{nt} + \sum_i \left(r_{ni} W_{n-1,it} - W_{nit} \right),$$

where streamflow F_{nt} equals previous streamflow $F_{n-1,t}$ plus additional rainfall and tributary inflow I_{nt}, net reservoir-release R_{nt}, upstream return-flow r_{ni}, and less diversions W_{nit}.

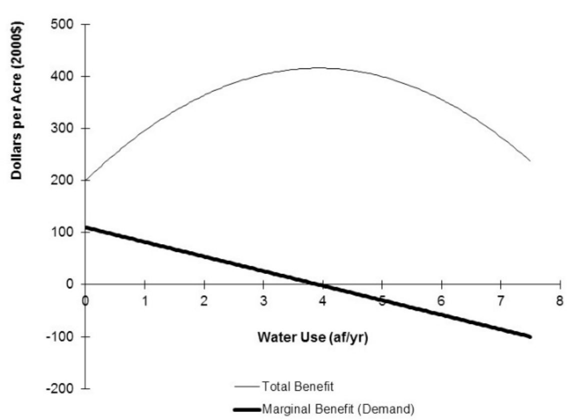
<FIGURE 10 ABOUT HERE>

Figure 10. Example of Annual Residential Water-Use Benefits from the Rio Grande Hydro-Economic Model: City of Albuquerque



<FIGURE 11 ABOUT HERE>

Figure 11. Example of Annual Agricultural Irrigation Benefits from the Rio Grande Hydro-Economic Model: Middle Rio Grande Conservancy District



Storage balance constraint. Equation (8) is an example storage balance constraint which maintains physical continuity and mass balance of reservoir and aquifer storage across time periods. It is important for optimizing inter-temporal tradeoffs between the value of current and future water use (i.e., marginal user cost, see Hotelling, 1931; Scott, 1953; Ciriacy-Wantrup, 1963; Burt and Cummings, 1970).

$$(8) \qquad S_{nt} = S_{n,t-1} + I_{nt} + \sum_i \left(n_{ni} W_{n-1,it} \right) - R_{nt} - L_{nt},$$

where storage S_{nt} equals previous period storage $S_{n,t-1}$ plus net additions from inflow I_{nt} and net-seepage from upstream diversions $n_{ni}W_{n-1,it}$, less net amounts pumped or released R_{nt} and evaporation losses L_{nt}.

The General Algebraic Modeling System (GAMS, Brooke et al., 1996) is the most common software platform used for the mathematical programming of hydro-economic models. Once objective and constraint functions have been appropriately specified and parameterized model testing, calibration and validation can proceed. Testing model consistency and parameter sensitivity requires careful examination of model output and inspecting it for deviations from performance expectations. Because of the extensive output GAMS reports, for example, the optimized values for each variable and constraint, post-optimization data processing is needed. For example, raw output for variables and elements of interest is transformed into summary variables that average and/or aggregate over sectors, regions and time periods.

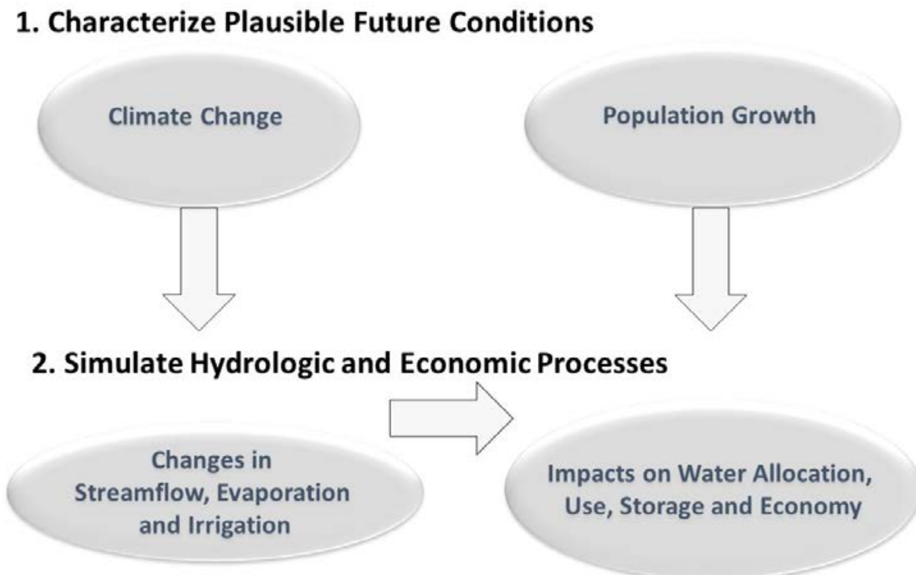
Hydro-economic models typically make two important assumptions. First, they assume water moves freely between water users, subject to modeled physical constraints, under a pseudo-competition that permits water to flow to ‘its highest valued use’, i.e., marginal value (shadow price) equalizes across uses. This assumption ignores, for example, institutional barriers, transactions and adjustment costs that would otherwise impede water transfers. Second, hydro-economic models generally optimize across many time periods. In effect, this multi-period perspective permits ‘perfect foresight’ in anticipating future climate patterns and inflows. As a result, optimized water use and storage estimates are perfectly adapted to hypothesized futures. Both of these assumptions tend to understate and present lower bound impact estimates.

b. Framework for Assessing Climate, Water and Socio-economics

Following testing, calibration and validation of the baseline hydro-economic model, the assessment process moves forward to develop linkages to other models and develop alternative scenarios (e.g., policies, programs, infrastructure, and management). The general conceptual framework shown in Figure 12 describes linkages relevant for climate change assessment. The process consists of two principle stages, scenario development, and model modification and execution. The principle drivers are future scenarios of both climate change and socio-economic change. These scenarios then inform both hydrology and hydro-economic models. For example, a hydrology model processes data on climate change and baseline streamflow to estimate resulting streamflow patterns input into the hydro-economic model.

<FIGURE 12 ABOUT HERE>

Figure 12. A Conceptual Framework for Modeling Climate, Water and Socio-economic Interactions and Economic Effects



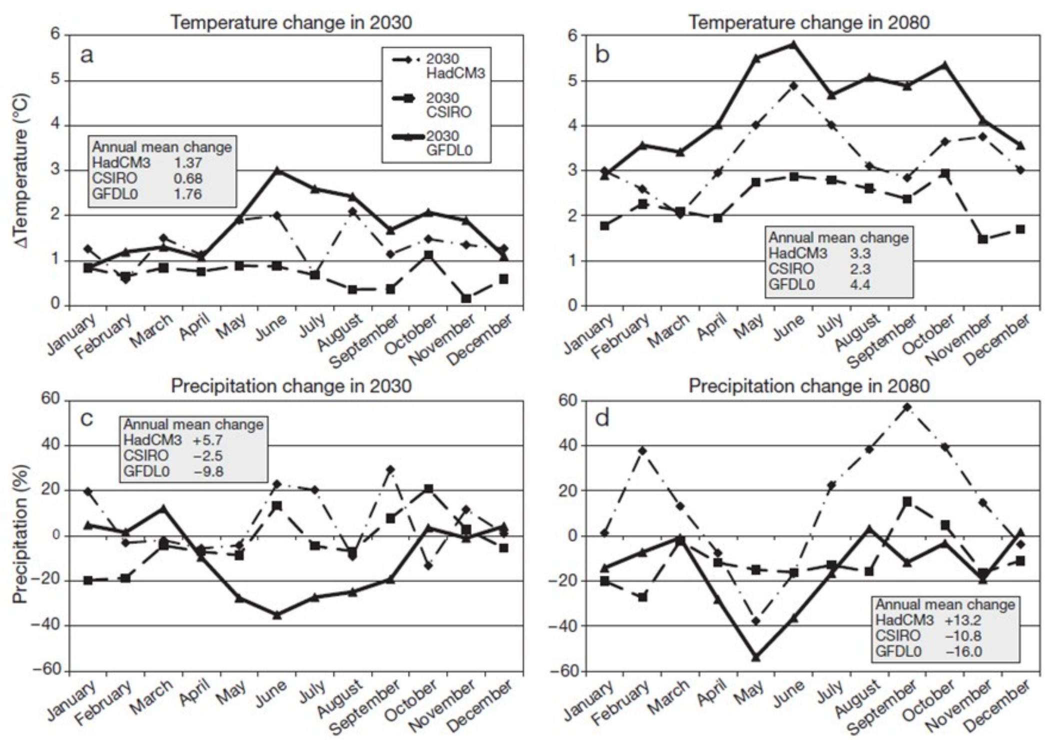
c. Identifying and Developing Scenarios of Climate Change

Climate change scenarios are the principle drivers of the assessment, and their development is guided by assessment goals, objectives and resources, in combination with available climate expertise. In general, a range of scenarios are developed that represent the plausible range and variation of projected regional changes. For example, in the Rio Grande assessment Hurd and Coonrod (2012), with expert help from Smith and Wagner (2006), selected three representative climate change projections from the IPCC Fourth Assessment Report's (Soloman et al., 2007) suite of 18 climate models (GCMs) under the relatively 'middle-of-the-road' emissions scenario commonly known as A1B.

Figure 13 summarizes the temperature and precipitation changes modeled for the Rio Grande assessment.

<FIGURE 13 ABOUT HERE>

Figure 13. Example of the Climate Change Scenarios used in the Upper Rio Grande Assessment: Modeled Temperature and Precipitation Changes for 2030s and 2080s



Note: All scenarios use A1B emissions. General Circulation Models (GCMs) used are the HadCM3 from Hadley Center for Climate Prediction and Research in UK Met Office, CSIRO MK3.0 from Common Wealth Scientific and Industrial Research Organization of Australia, and GFDL0 from National Oceanic and Atmospheric Administration's (NOAA) Geophysical Fluid Dynamics Laboratory.

d. Constructing Scenarios for Socio-Economic Trends and Baseline Changes

As climate change evolves over time, so do communities and economies. Regional population growth, some studies suggest, could amplify exposure and vulnerability to risks from severe droughts and flash floods (e.g., Hurd et al., 1999b, 2004). For consistency in comparing model outcomes, trends of future population and economic change are modeled along with scenarios of future climate change. A comparable scenario of a plausible future baseline is constructed that models future population and economic change but maintains current climate. This 'baseline scenario' then forms the basis for climate change comparisons (Malone et al., 2004).

To account for socio-economic trends, and in particular population growth, domestic water demands in the hydro-economic model should shift accordingly. In addition to population growth, some studies report income-induced shifts in water demand (e.g., Espey et al., 1997; Hanemann, 1998; Hewitt and Hanemann, 1995; Martinez-Espineira, 2004). Hurd and Coonrod (2012) ignored income effects, finding that regional income elasticities were generally low and potentially offset by trends showing increasing household water-use efficiency.

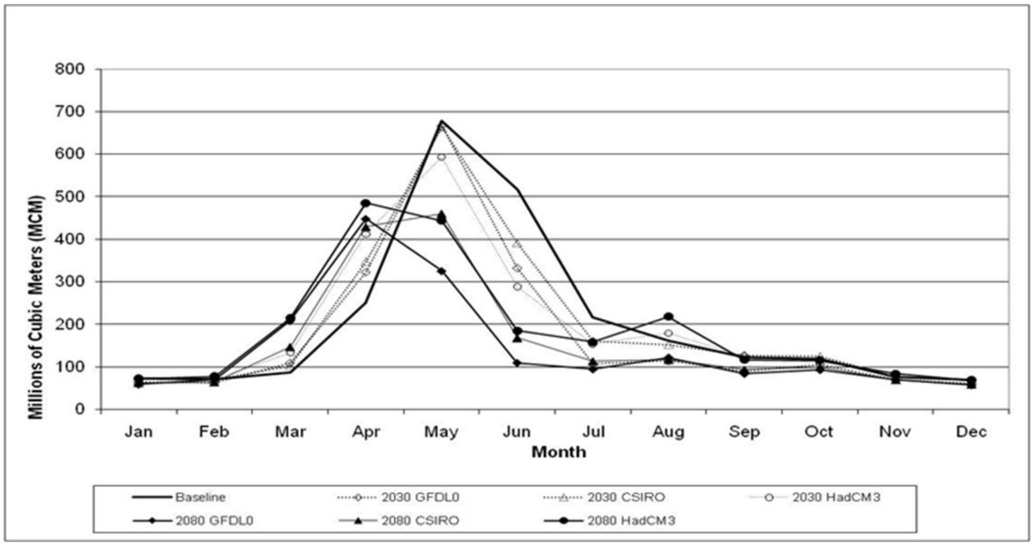
e. Hydrology Modeling and Streamflow Changes

Many assessments demonstrate watershed sensitivity and vulnerability to climate change (e.g., Barnett et al., 2004; Christensen and Lettenmaier, 2007; Christensen et al., 2004; Elsner et al., 2010; Milly et al., 2005; Nohara et al., 2006; Cai et al., 2003; Gleick et al., 1997; Medellin et al., 2009). Various hydrology models and approaches are available, from highly simplified response-surface models linked to temperature and precipitation change to highly specified and calibrated variable infiltration-capacity (VIC) models (e.g., Lettenmaier et al., 1999; Leung and Wigmosta, 1999; Littell et al., 2009; Cai et al., 2003; Harou et al., 2009; Hurd and Rouhi-Rad, 2013; Pulido-Velazquez et al., 2006).

Both types have been used effectively in climate change assessments and estimate streamflow changes from climate change scenarios. Hurd and Coonrod (2012) use estimates from a simplified model, WATBAL, which simulates changes in soil moisture and runoff as a result of changes in temperature and precipitation (Yates, 1996, 1997). Figure 14 illustrates projected streamflow for each of the climate scenarios used in the Rio Grande assessment (Hurd and Coonrod, 2012). In contrast, Bui (2011) estimated Rio Grande streamflow changes using the U.S. Army Corps of Engineers Hydrologic Modeling System, which simulates precipitation and runoff processes applicable to a wide range of watersheds (HEC-HMS, Scharffenberg and Fleming, 2003, 2010).

<FIGURE 14 ABOUT HERE>

Figure 14. Example of the Modeled Streamflow Changes from the Upper Rio Grande Assessment



f. Climate Effects on the Hydro-Economic Model

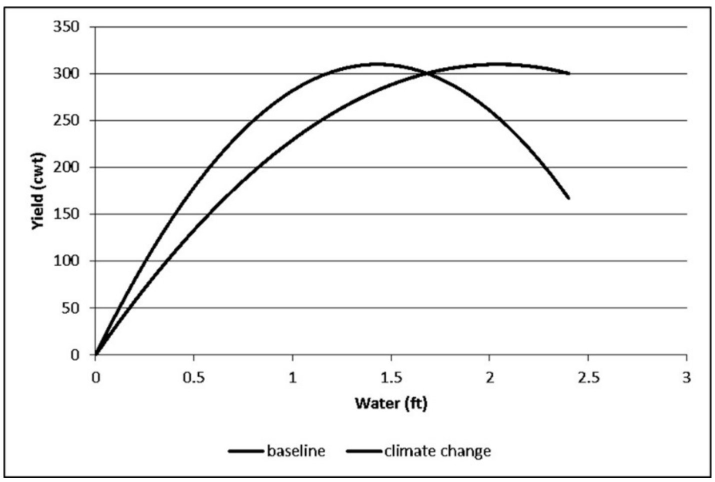
Climate change alters both water supply and demand across a watershed, and the hydro-economic model combines and integrates data and information for both. Hydrology model estimates of primary water supply changes (e.g., inflows and evaporation) drive water supply changes in the hydro-economic models. Water demand changes, however, must be input directly with appropriate temperature-driven adjustments to all benefit and cost functions and constraints as necessary (e.g., Hurd and Rouhi-Rad, 2013; Hurd et al., 1999; Hurd et al., 2004; Hurd and Coonrod, 2012; Lund et al., 2003; Medellin et al., 2008; Pulido-Velazquez et al., 2006).

For example, higher temperatures will raise consumptive irrigation requirements for most crops, including residential turfgrass. To reflect evapotranspiration changes,

changes in crop-water benefit functions are matched to temperature changes given by specific climate-change scenarios. An example of this change is illustrated in Figure 15 as temperature increase causes a right-ward shift in required irrigation needed to maintain yield productivity.

<FIGURE 15 ABOUT HERE>

Figure 15. Example of Modeling the Effects of Climate Change on Crop Irrigation Productivity



CONCLUSIONS

This chapter demonstrates that assessing the economic consequences of climate change on watersheds and water resources is a highly involved process. Significant efforts in assessment design, data development, and model execution are necessary for success. By describing and detailing the assessment process, beginning with economic foundations of value and measurement, proceeding to elements of hydro-economic modeling, and finally presenting an overview of integrated climate-water assessment, this chapter develops several key points summarized by the following:

1. Economic value is an important and more useful concept for effective and efficient climate and water resource management than other metrics, including 'water footprints,' virtual water, and general economic impacts (e.g., GDP, jobs, income).
2. Water generates economic value in many direct and indirect ways. Water is an important input into the production of varied products and services including food, energy, and manufactured goods.
3. Water markets and prices are incomplete indicators of water's real economic value because of government intervention and market failure (e.g., externalities, public goods, and incomplete resource markets).
4. Climate, water and human systems are complex and highly interconnected systems that present many challenges for effective policy and management. Integrated models, including hydro-economic models, are powerful approaches that can yield insight and improve understanding necessary to develop appropriate mitigation actions and adaptation strategies.
5. Hydro-economic models can be effective tools and approaches; however, care must be given to their construction and use. Data development is crucial and there are many elements and relationships requiring careful specification.

6. A clearer understanding of economic foundations, concepts and approaches not only improves assessment design and execution, but the interpretation and communication of results and findings.

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LIST OF FIGURES

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