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January 1, 2013

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Abstract

The U.S. Environmental Protection Agency (EPA) has embarked on an effort to better understand the importance of water in the U.S. economy. To date exclusive emphasis has been placed on the relationship between water and the market economy, particularly with regard to water-related activity that shows up in national accounts. A market-based accounting approach implies seeking out the traded value of product, price multiplied by quantity, and water-related capital investment. In this paper I analyze the effectiveness of this approach in capturing the importance of water in the U.S. Economy. I develop stylized models of consumer and producer demand and use them to derive economic values for water. I then turn to the impact of rationing on the economic value of water and provide an optimal decision rule for rationing. I extend consumer demand to incorporate natural water, water supplied by nature through rain and snow. I derive economic values under varying levels of natural water and investigate the impact on inferring demand elasticities when natural water is unmeasured. Using findings from the literature regarding prices charged for water, I explore economic inferences that can be drawn from market-based accounting measures.

1 Introduction

In 2012, the U.S. Environmental Protection Agency (EPA) conducted a study on the importance of water in the U.S. economy.[1] The stated intent of the report was to "summarize existing knowledge on the topic; provide information that supports private and public sector decision-making; and identify areas where additional research would be useful." Methodologically, "the study focuses exclusively on the relationship between water and the market economy - the water-related economic activity that is captured in national economic accounts." A market-based accounting approach implies seeking out the traded value of product, price multiplied by quantity, and water-related capital investment. In this paper I analyze the effectiveness of this approach in capturing the importance of water in the U.S. Economy. In particular I focus on the inferences that can be draw and their relation to public sector decision-making.

2 Vital Statistics on U.S. Water Use

The most recent estimates of water use in the U.S. are for 2005 and reported by the United States Geoglogical Survey (USGS [8]). From this report, daily withdrawls of water in the U.S. are estimated to be 410 billion gallons per day (Bgal/day). Of these withdrawls, saline water withdrawls are 61 Bgal/day

[1] The report is titled "The Importance of Water to the U.S. Economy Part 1: Background Report" [11].

and freshwater withdrawls are 349 Bgal/day. Across all withdrawls, percentage uses are as follows: thermoelectric - 49%; irrigation - 31%; public supply - 11%;industrial - 4%; aquaculture - 2%; mining - 1%; and domestic[2] (households) - 1%.

Groundwater plays a very significant role, accounting for 20% of total withdrawls and 23% of freshwater withdrawls. By use, ground water accounts for 1% of thermoelectric withdrawls, 42% of irrigation withdrawls, 33% of public supply withdrawls, and 98% of domestic withdrawls. Of course there is considerable variation across states of the proportion of ground water withdrawn.

3 Modeling the Value of Water

I first want to develop a simple model of consumer demand for water that I can use to derive the consumer's value for water. I will follow with a similar development for a producer.

3.1 Consumer Value of Water

Consumers use water for a variety of reasons such as drinking, personal hygiene, cooking, and watering landscape. Although we typically only observe a household's total demand at an observation point, such as monthly demand,

[2]The USGS report defines domestic use as water used for indoor and outdoor household purposes. Water can either be supplied by a public supply system or be self-supplied. Note domestic use is not included in public supply use, even when supplied by a public supply system.

conceptually we can think of water demand for each service provided.[3] Services are what the household values and they are provided through a household production function that for sake of simplicity only depends on water w_i, $z_i = f_i(w_i)$. The consumer's problem is to maximize utility by choosing how much of a composite commodity x to consume and how much water to purchase for each service at delivery price, p_w, subject to a budget constraint $Y = x + p_w \left(\sum_i w_i\right)$ where Y is income. Total household demand for delivered water is the sum of water demands used as inputs to produce the various services, $w_h = \sum_i w_i$. Equation (1) states the problem.

$$\underset{x,\ \{w_i\}}{max}\ U(x, z_1, ..., z_I)\ s.t.\ Y = x + p_w \left(\sum_i w_i\right), z_i = f_i(w_i), i = 1, ..., I \quad (1)$$

The optimization problem results in a set of optimal demands for water inputs for each service, $w_i(p_w, Y)$. Note that as we raise the price, some demands will fall to zero which results in a consumer's total demand curve, obtained by summing over water demands for services, being kinked. We could consider uncompensated consumer surplus, the sum of the areas between the demand curves and price, as a measure of value. However as we move up the demand curves as price increases, utlity goes down. Therefore using uncompensated consumer surplus as a measure of value will not deliver a proper value, though

[3] In future versions of this paper I intend to pursue additional work using this multi-service approach. This version of the paper does fully utilize this approach other than in exposition.

it can serve as an approximation. As price rises consumers require more compensation than the change in uncompensated consumer surplus. Similarly if price were to decrease, uncompensated consumer surplus would have the consumer paying too much for the price decrease. To derive a proper measure of value, I turn to the dual problem that produces a proper measure of value through compensated demands.[4] Compensated demands are central to welfare analysis since they provide monetary measures tied to a reference utility level. The dual consumption problem requires minimizing expenditures on the composite commodity and water demands for each activity while maintaining a given utility level U. The solution to this problem is a set of optimal compensated, Hicksian demands for water for each activity, $w_i^h(p_w, U)$.[5]

$$\min_{x,\ \{w_i\}} x + p_w \left(\sum_i w_i \right) \ s.t.\ U = U(x, z_1, ..., z_I), z_1 = f_1(w_1), ..., z_I = f_I(w_I) \tag{2}$$

For the purposes of welfare analysis, we use the compensated demands as measures of total value for water in that activity as depicted in Figure 1.

Given the single price for water across activities, we can aggregate across these demands to derive the consumer's total compensated water demand by horizontal summation of demands. Given the one price for water across

[4]Compensated surplus is the exact amount of compensation required to accept the price increase.

[5]The multi-service approach I am using here can accommodate individual prices for different services that can be very analytically useful.

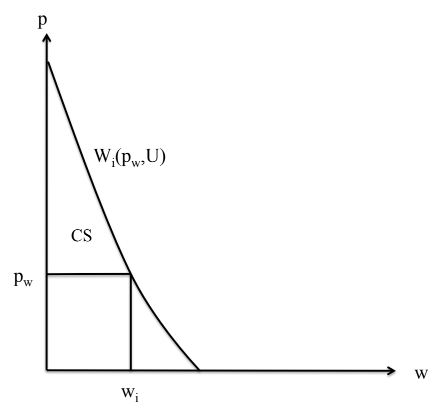

Figure 1: Total Value/Consumer Surplus for Water Input to Service i

these activities, the total value for water is the sum of surpluses over the compensated water demands. If water is an essential input to these various services, if we raise the price enough, demand for water goes to zero and those services disappear if there is no substitute source.

$$Total\ Consumer\ Value\ of\ Water = \int_{p_w}^{\infty} \sum_i w_i(s,U)ds \tag{3}$$

3.2 Producer Value of Water

Producers use water as an input to production and they operate so as to maximize their profits defined as revenue from sales minus total cost of production. To develop a simple stylized model of production and profit maximization, I will consider production technology with two inputs: water, w, and a composite input z. Production technology for commodity Q is a function of these inputs, $Q = F(z, w)$. Like the consumer problem presented above, we can view the problem from two different angles. One approach posits a cost minimization problem subject to an output level. Solutions from this problem lead to a cost function that depends on output level and input prices. The derived cost function links output to minimized costs. This approach is handy for characterizing the level of output in the commodity space. Given minimized costs, the producer maximizes profit by choosing the best level, where marginal revenues from production equal marginal production costs. The cost function also has nice symmetry properties that facilitate econometric estimation of input demands. A different approach, the one I use, solves the profit maximization in choice of inputs subject to input prices and the market price for Q, P_Q. I am choosing this second route because of a nice graphical representation that links demand for water to a proper value measure. I assume a perfectly competitive market. Here is the profit maximization problem.

$$\underset{z,\, w}{max}\; \pi(z, w) = P_Q F(z, w) - z - p_w w \tag{4}$$

It is worth writing down the first order condition for the choice in w and recognizing that the marginal revenue from additional water equals its price.

$$P_Q \frac{\partial F(z,w)}{\partial w} = p_w \tag{5}$$

The solution to this maximization problem provides a set of optimal inputs, $\{z(p_w, P_Q), w(p_w, P_Q)\}$ that can be used to derive a value function for profits.

$$\pi^*(p_w, P_Q) = P_Q F(z(p_w, P_Q), w(p_w, P_Q)) - z(p_w, P_Q) - p_w w(p_w, P_Q) \tag{6}$$

What is the contribution of water for the producer? Like the consumer, we want to think about life without water while making them whole. That is, we want to calculate the change in profits. Similar to the consumer problem, we seek to price them out of water. Let p_w^c equal the price that accomplishes this. Then our measure of value of water is given as follows.

$$Total\ Producer\ Value\ of\ Water = \pi^*(p_w, P_Q) - \pi^*(p_w^c, P_Q) \tag{7}$$

Again we can derive a compact intuitive result. Using the fundamental theorem of calculus we can write the difference in profits resulting for the change in the price of water.

$$Total\ Producer\ Value\ of\ Water = \int_{p_w^c}^{p_w} \frac{\partial \pi^*(s, P_Q)}{\partial w} ds \tag{8}$$

We can apply the envelope theorem to equation (6) which implies that if we differentiate the value function with respect to the parameter p_w, the derivative is the of the value function where w_p directly enters the value function.[6] Finally we can rewrite the change in profits as an area under the input demand curve.

$$Total\ Producer\ Value\ of\ Water = \int_{p_w}^{p_w^c} w(s, P_Q)ds \tag{9}$$

Again let's consider the case when water is absolutely essential to production. In this case, the change in profits exactly equals profits from production *in that activity at that location.* A plant can shut down and move making the notion of proper compensation a bit trickier. For irrigated farms, we could consider the difference between profits for irrigated versus unirrigated farming.[7]

3.3 Value of Water and Rationing

In most years, a significant portion of the nation suffers from drought. Despite managers' best efforts to organize water delivery to meet demand, supply shortages at prevailing prices are commonplace. From the standpoint of economic efficiency, prices should be raised to scale back demand so the market exactly clears. Using price to alleviate shortfalls ensures the water finds its way to the most valued uses. However most public water suppliers

[6] Some of the most celebrated uses of the envelope theorem in economics are the derivation of Shephard's lemma and Roy's identity.

[7] A farmer's income is not equivalent to profit because it includes the value of the farmer's labor input (Hanemann [6]).

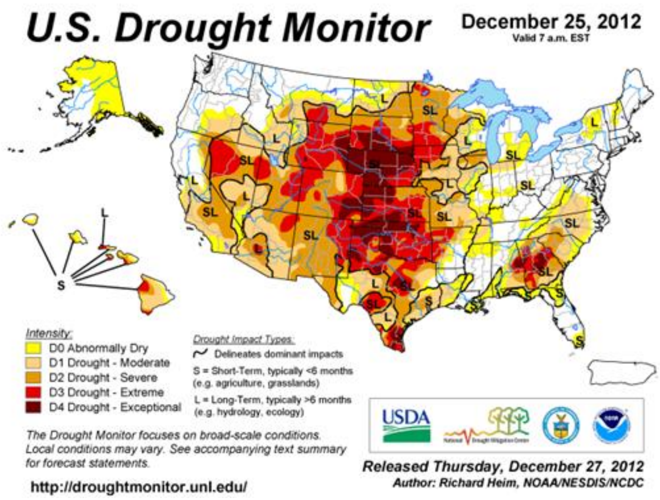

Figure 2: Drought in the U.S.

are reluctant to use price to allocate scarce water and instead implement voluntary or mandatory cutbacks, often proportional to demand.

For consumers and producers, the marginal cost of the rationing constraint is simply the difference between inverse demand at the ration point w^r and the price of water.

$$Marginal\ Rationing\ Cost = p^v(w^r) - p_w \tag{10}$$

Let U^D equal the consumer utility level when demand is met. The amount of compensation required to keep the consumer at the unrationed utility level is the integral of inverse demand minus price from the rationed to unrationed levels of water.

$$Total\ Consumer\ Rationing\ Cost = \int_{w(p_w,U^D)}^{w^r} p^v(s,U^D) - p_w\ ds \qquad (11)$$

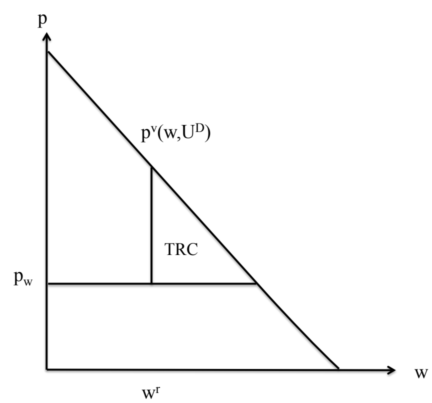

Figure 3: Total Rationing Cost

The total value of water to a consumer under rationing is not the rest of the area between the compensated demand curve from and price from above because with rationing, utility goes down, $U^r \leq U^D$. For this reason the value of water takes the following form.

$$Consumer\ Total\ Value\ Rationing = \int_{w^r}^{\infty} p^v(s,U^r) - p_w\ ds \qquad (12)$$

The profit loss to the producer is similarly represented in intergral form while the profits from the use of water are the remainder of the surplus.

$$Total\ Producer\ Rationing\ Cost = \int_{w(p_w,P_Q)}^{w^r} p^v(s, P_Q) - p_w\ ds \tag{13}$$

$$Producer\ Total\ Value\ Rationing = \int_{w(p_w,P_Q)}^{w^r} p^v(s, P_Q) - p_w\ ds \tag{14}$$

Efficient rationing is characterized by the following condition.

$$p_i^v(w_i^r) - p_w = p_i^v(w_i^r) - p_w\ \forall i, j \tag{15}$$

To acheive efficiency we need to understand how inverse demand changes in response to the level of rationing. In Flores and Carson [1], we showed that for a set of rationed demands, the compensated quantity elasticities of price/inverse demand are inversely related to the compensated price elasticities of demand. In the case where only w is rationed, then the quantity elasticity of price is simply the inverse of the price elasticity of demand. In this case we can determine how much price goes up as w is rationed. If price elasticity of demand is -0.2, then the quantity elasticity of price is -5. Thus a 1% reduction in water by rationing results in a 5% price increase.

Knowledge of users' quantity elastitices of price allows us to derive optimal allocation rules. Consider the case of three consumers and we know their quantity elasticities of price $\{\sigma_1^v, \sigma_2^v, \sigma_3^v\}$. In order to enforce efficiency, we want to keep inverse prices equal as we ration. Starting from the point where demand is met, for a one percent reduction in water for the first user, we would need a σ_1^v/σ_2^v percent reduction in user two's water and a σ_1^v/σ_3^v percent reduction in user three's water. This simple rule of thumb equates the net marginal benefit of water across users, maintaining efficiency similar to a price mechanism. This rule of thumb also works across markets served by the same provider. For example if a supplier had to ration between two groups that have different delivery prices, *e.g.* irrigated farming and residents, we would still want to equate the marginal cost of rationing as we moved them away from the point where market demand is met. When market demand is met, price equals demand and so across markets without rationing the net benefit is zero. When we ration across the markets, the changes in inverse prices are what matter, not the prices charged for delivery in the markets provided prices charged to not change as a result of rationing.

Using the simple rule of thumb, we can figure out how big of a percentage reduction in water for the reference consumer, consumer one in this case, is required to efficiently meet the rationing target. Denote consumer i's share of total market demand by S_i. Now suppose we want a P% reduction. It is fairly simple to derive that would need a $P/[S_1 + \frac{\sigma_1}{\sigma_2}S_2 + \frac{\sigma_1}{\sigma_3}S_3]$ percent reduction for consumer one to accomplish the overall demand reduction if we are using the optimal rationing rule.[8]

[8]I have presented things for individual consumers. You can easily apply the rule to

If we are interested in account values for water, adjustments need to be made whenever there is rationing in order to make correct inference regarding the marginal value of water to consumers. We can estimate how much the marginal value changes relative to the price using the inverse elasticity. For example Klaiber *et al.* [9] estimate price elasticities of demand for residential consumers in Phoenix for five consumption percentiles for summer and winter demand. Summer demand elasticites vary significantly across deciles from -.45 to -.99 for one set of estimates and -.13 to -.35 in another set of estimates.[9] Using the second set of demand elasticities, we have quantity elasticities of price that range from -7.6 to -2.8. Given the compounding effect, a 10% ration level results in price increases ranging from 40% to 100%. Given the frequency of drought and rationing, accounting values that are not based on adjusted prices will seriously underestimate the marginal value of consumption.

3.4 Valuing Natural Water

According to the USGS, in 2005 agriculture accounted for 31 percent of water withdrawn in the U.S. Approximately one third of household use is for outdoor uses, primarily for landscape watering. In considering consumptive use rather than withdrawls, agriculture accounts for over 80 percent of water consumed. On the other side of the coin, according to the latest farm census

groups of consumers who share elasticities.

[9] The authors derive their estimates using data from different years. The percentile range that is more inelastic is estimated from data with drier conditions.

conducted by the U.S. Department of Agriculture in 2008, only 27% of total farmland in the U.S. is irrigated.

These statistics led me to think of a different valuation problem that is not being discussed: the value of water in the U.S. economy for water that is not moved at all, but simply falls from the sky and puts moisture on crops and lawns. To this end I want to modify the model of consumer demand to account for water from the heavens. This falls outside of the scope of water traded in markets, but I believe the problem fits well in the big picture due to the close interaction with markets.

Again the consumer's problem is still to maximize utility by choosing how much of a composite commodity x to consume and water w. What changes in the problem is I now consider natural water that is provided at not charge by nature. Now $x + p_w(w - w_N) = Y$ where w_N is natural water provided free of charge.

$$\underset{x,\, w}{max}\ U(x, z_1, ..., z_I)\ s.t.\ Y = x + p_w \left(\sum_i w_i - w_N \right), z_i = f_i(w_i), w \geq w_N \tag{16}$$

We can think of demand for withdrawn water for outdoor residential use as supplementary supply to natural water. It is easy to see by the way that I have written the problem out, that the amount of compensation required to give up a given level of natural water is simply the market value of the water. That is the total value of the natural water alone is $p_w w_N$. As we add natural water, total household demand will increases slightly due to an income effect. Letting U^N equal the utility obtained with natural water the total value of water can be represented using the compensated demand curve.

$$Total\ Value\ of\ Water\ |Natural\ Water = \int_{p_w}^{\infty} \sum_i w_i(s, U^N)ds\ + p_w w_N \tag{17}$$

As w_N increases, the value of water approaches the total area under the compensated demand curve, a situation where the marginal value of water is zero.[10]

An interesting result comes out of this model. Consider the price elasticity of demand.

$$\sigma^w = \frac{\partial w}{\partial p_w} \frac{p_w}{w} \tag{18}$$

In the model I have written down, the price elasticity of demand would remain roughly constant for the *full* amount of water w regardless of the amount of natural water.[11] However demand for delivered water is the difference $w - w_N$. Let's suppose that in dry times there is no natural water. Inference regarding elasticity of demand is given by σ^w above. In normal times demand elasticity would look as follows.

[10]I would like to extend this model to include too much water, where additional water has a negative marginal value.

[11]I am assuming away temperature differences that may also vary with the level of w_N.

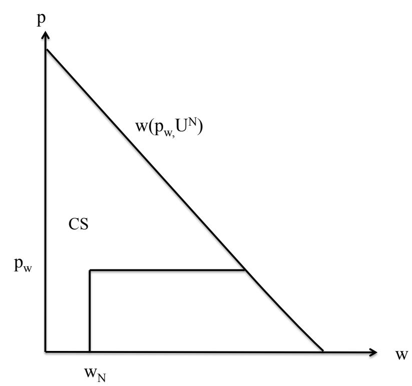

Figure 4: Total Value/Consumer Surplus for Water|Natural Water

$$\sigma^w_{normal} = \frac{\partial w}{\partial p_w} \frac{p_w}{(w - w_N)} = \sigma^w \left(1 - \frac{w_N}{w}\right)^{-1} \tag{19}$$

The elasticity observed under normal times when there is natural water present is simply the dry times elasticity scaled by the inverse of the share of delivered water of the full amount of water w. With more natural water, observed demand will appear more elastic than in dry times which is roughly consistent with the estimates from Klaiber *et al.* [9].

3.5 Proper Inference of Economic Values

The consumer and producer values presented above are considered by most economists to be the proper measures of private value for those purchasing water. I use the pharse private value because I am not jointly analyzing problems of externalities in this paper, rather emphasizing values reflected in the market. As the analysis suggests, knowledge of the price elasticities of demand and their counterparts, the quantity elasticities of price under rationing, are of first order importance. Management decisions should be about tradeoffs. Understanding the economic impacts of these tradeoffs requires knowledge of the behavior on the margin, of market demands.

4 Water Prices

The cost of water is dominated by capital costs since the main costs are for transport and treatment. As noted by Hanemann [6], most water providers receive water at no cost. Near zero input price coupled with the capital intensive nature of transport and treatment leave us with a commodity that has very low marginal delivery costs but relatively very high capital costs. The general consensus in the literature (Olmstead [12]) is that pricing at long-run social marginal costs is efficient. Long-run social marginal costs include current marginal delivery costs, any externalities, efficient maintenance and growth of capital costs, and scarcity rents, present and future. As noted by many economists[12], the unit price charged for water is far from efficient. The Federal and various state governments regularly subsidize infrastructure in agricultural water, and wastewater treatment resulting in one major source

[12] For examples see Griffin ([5], [4]), Gibbons [2], and Hanemann [6].

of pricing inefficiency. Generally speaking U.S. water and waste water infrastructure maintenence is severely underfunded,[13] indicating that maintenance and growth of infrastructure is not being covered.

As the summary statistics in section 2 indicate, groundwater plays a very important role in the nation's water supply. While groundwater is technically a renewable resource, extraction rates in many areas exceed recharge rates, effectively turning water in those aquifers into a non-renewable resource.[14] Furthermore groundwater interacts with surface water. Groundwater extraction can have a negative impact on surface flows and in coastal areas excessive groundwater extraction can lead to saltwater intrusion. Prices of groundwater generally do not reflect non-renewable resource scarcity nor do they reflect externalities from surface water interactions.[15] There also exists a problem of the commons. Those extracting groundwater from a common pool have no incentive to hold back from pumping to the point where the current marginal value equals marginal pumping costs. For all of these reasons, the marginal price paid for groundwater falls far below the socially efficient price.

[13]The American Society of Civil Engineers [7] cites a \$55B shortfall in infrastructure investment. Maxwell and Yates [10] further elaborate on this problem .

[14]Gleeson *et al.* [3] provide new statistical evidence on the degree of groundwater mining in the journal *Nature*.

[15]As an exception, in the last decade Colorado transitioned wells into the property rights system. Well owners have junior rights and may be subject to calls that require cessation of pumping when more senior rights are threatened.

5 Accounting Values

The previous sections provided a conceptual overview of the economic value of water and price charged from a conventional welfare economics perspective. Now I turn to the use of market-based account values as economic indicators to provide useful information in support of private and public decision making.

Information on withdrawls, consumption, prices, and capital expenditures is crucial for meaningful economic analysis of water use and management in the U.S. Researchers and decision makers need access to reliable and accurate data. I applaud EPA for their new efforts in this area. I am, however, concerned about reliance on account values for a number of reasons.

Observed prices are fraught with problems since they do not come close to reflecting marginal social costs. All indications suggest prices are systematically low. Thus observed price by quantity measures are for inefficient outcomes. In cases where all market demand is met, prices do reflect the private marginal benefit of use. However when there are demand restrictions, something that many millions of Americans face in a typical summer, price no longer signals the marginal benefit of use. Given estimates of demand elasticities from the literature, marginal values could easily be twice the market price in times of rationing.

Knowledge of capital depreciation and investment is crucial for getting a clear picture of the economics of water in the U.S. Groundwater as a depletable natural resource is an important form of capital that is not being accounted for in market-based capital accounts. For over twenty years economists[16] have stressed the need to adjust national accounts to reflect the depletion of natural resource stocks. Given the scale of groundwater extraction in the U.S., 79.6 Bgal/day, this depreciation is likely significant. For this reason relying on market based capital expenditures without groundwater depreciation could be very misleading.

Finally, accounts of all water market expenditures, including those by producers, has no economic interpretation other than market expenditures. There is a reasonably large literature on the interpretation of net national product as an indicator of well being. This literature began with Weitzman's [15] seminal article showing that along an optimal consumption and investment path, net national product is proportional to the sum of present value discounted utility. Much of the subsequent work focused on extending this work to include natural resource and environmental depreciation as well as relaxing Weitzman's underlying assumptions. Net national product is the value of all final goods and services in the economy minus depreciation. The green accounting literature calls for extended net national product to include environmental depreciation. Most of the water withdrawn in the U.S. is used for production. The consumption value of water is therefore reflected in products that are consumed. Intermediate inputs do not enter net national product because this would be double counting. Thus the ma-

[16]See Peskin [13] for an early treatment or for a comprehensive overview Repetto [14].

jority of water expenditures, other than net capital depreciation, would not be part of this welfare measure.[17] In summary, market based expenditures are not particularly good indicators of the economic contribution of water to the economy though that the data is important for conducting meaningful economic analysis.

6 Looking Forward: Research

It is both important and useful to understand the economic contribution of water to the U.S. economy on a big scale. Population growth coupled with climate change suggest the future of water supply and management will be considerably more challenging than the past. Supply systems are suffering from under investment in capital even given current population.

Making the tough choices will require a reasonable understanding of what is involved in the economic tradeoffs. Though important data, market-based expenditures hold little promise for guiding decisions. Carefully selected, detailed economic studies would be extremely useful. I can envision a set of studies that are either regionally or watershed-based that drill down into the data, even collecting original data, working to credibly estimate demand elasticities, and estimating the impact of shortages and perhaps even overages (flood). A properly done set of regional studies could provide information to be used in benefits transfer to other areas. This would give decision mak-

[17] It is worth noting that all of the results from the net national product/adjusted net national product literature assumes consumption and investment are optimal over time.

ers some insight into how alternatives may affect their constituents and help guide them to more efficient outcomes. Estimates from sample studies could be used to interpret market-based expenditure data from across the nation and get a more credible estimate of the value of water and its economic contribution. Finally, the impact of water quality and quantity on the environment and recreational should be integrated into this framework.

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