The Importance of Tariff Structure in Conservation Pricing

by

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Introduction

Over the last decade, price has received increased emphasis as a policy tool in irrigation water management. Irrigation districts in the largest federal water project, the Central Valley Project (CVP) are required to adopt "conservation pricing" under the terms of the Central Valley Project Improvement Act, and the United States Bureau of Reclamation (USBR) promotes adoption of "conservation pricing" by irrigation districts in other areas as a best management practice (USBR, 1998).

The prices promoted by the USBR are volumetric prices (measured as dollars per acre-foot of water demanded), and most research examining the consequences of adopting conservation prices measure water prices in this way (Huffaker et al., 1998; Caswell, Lichtenberg, and Zilberman, 1990). Unfortunately, irrigation districts generally do not use volumetric prices (Michelsen et al., 1999). Most irrigation districts in the western United States charge for irrigation water through acreage fees, not through fees on the quantity of water demanded. This divergence between the theory of conservation prices and the actual practices of irrigation districts has significant implications for water conservation policy development.

Since irrigation districts typically charge for water based on acreage, adopting conservation prices will require moving from an acreage-based fee structure to a volumetric pricing system. This is a change in tariff structure, not simply of price. The demand consequences of changes in tariff structure have been well-studied in non-agricultural contexts (Oi, 1971), but have not been extended to irrigation water. The present research examines the problem of conservation pricing of irrigation water as movement from a one-part tariff (acreage-based fee) to a two-part tariff (combination of acreage and volumetric water fees). As such, this research more closely parallels the actual institutional structures observed in irrigation districts across the western United States and provides a better measure of the conservation potential of pricing reforms across the West.

Theoretical Model

The analysis begins by discussing the on-farm irrigation decision of an individual irrigator. The irrigator obtains irrigation water from a regional irrigation district. The irrigator purchases water from the district through a two-part tariff. The first part of the tariff is an acreage fee, denoted *h*, which entitles the irrigator to receive water. When the irrigator purchases water for delivery, she pays the volumetric price *r* on whatever quantity of water she purchases.

The quantity of water applied by the irrigator to all crops is denoted *AW*. *AW* is determined by decisions at both the extensive and intensive margin. At the extensive margin, the irrigator chooses which of *k*-crops to produce and how many acres will be allocated to each crop. At the intensive margin, the irrigator determines how much water to apply to each crop given the acreage allocated to that crop. If l_k is acreage allocated to the *k*-th crop and AW_k is the water applied to that crop, then total water demand for the irrigator is:

1) $AW = \sum_k AW_k\left(r, l_k\left(p_k, h, r\right)\right)$

where both water and acreage allocations are specified as functions of the two prices for water use. Additionally, acreage is assumed to be a function of the output price for the *k*–th crop, p_k.

Simultaneous changes in *h* and *r*, such as might occur through adoption of conservation pricing, will affect *AW* in different ways. Totally differentiating equations 1) with respect to *h* and *r* shows:

2) $$d\,AW = \sum_k \left(\frac{\partial AW_k}{\partial r} + \right) dr + \left(\frac{\partial AW_k}{\partial l_k} \right) \frac{\partial l_k}{\partial r} dr + \sum_k \left(\frac{\partial AW_k}{\partial l_k} \frac{\partial l_k}{\partial h} \right) dh$$

The effects of changing the tariff structure faced by the irrigator leads to three separate forces acting on the volume of applied water. The first is the intensive margin impacts as the irrigator changes water applications to existing crop acreages due to a change in the volumetric price of water. The second and third effects both occur at the extensive margin as acreage changes in response to changes in the volumetric price of water and the acreage-based fee. The second term in equation 2) shows how water applications change as acreage is reallocated in response to a change in *r*, while the third term shows how water applications change due to acreage reallocations in response to a change in *h*. While both intensive margin water use and extensive margin land allocations are decreasing in *r* and *h*, if the two prices move in opposite directions (i.e., one price rises while another falls), the effects on water application are unpredictable.

Determining how changes in an irrigation district's tariff structure impacts actual water usage must be measured in terms of both water application and acreage allocation responses. Evaluating how irrigators allocate the land and water available to them through their production decisions can do this. To start this, it must first be recognized that irrigation systems are rarely perfect and some portion of AW_k will not be consumed by the crop to which the water is applied. The fraction of AW_k that is effectively conveyed to the crop for consumption is measured by irrigation efficiency. Irrigation efficiency is denoted d. Irrigation efficiency will be a function of the type of irrigation system used (denoted *it*), the attributes of the farm (denoted θ), and both the acreage fee *h* and the volumetric charge *r*, or

3) $$d = d(it, h, r, q)$$

While variations in both water-related prices may prompt adoption of alternative irrigation technologies, the present analysis assumes that irrigators will respond to price variation through changes in management of their existing irrigation systems. For this reason, it is assumed that δ is an increasing function in both r and h.

Given the presence of d, production of each crop will not be a function of applied water AW_k but rather is a function of effective water (EW_k) where EW_k is given by:

4) $EW_k = dAW_k$

EW_k is an increasing function of applied water and irrigation efficiency.

For each of the k crops, grower production is a quasi-concave function of effective water demand and is specified as $f(EW_k)$. The output price for each crop is p_k, so the irrigator's expected profits from all crop production are:

5) $$\max_{l_k, AW_k} \Pi = E\left\{\sum_k \left(p_k f\left(EW_k\right) - rAW_k - hl_k\right)\right\}$$

Two important things need to be said about equation 5). The first is to note that while production is a function of effective water, the irrigator actually pays for applied water. As a result, applied water will be the measure of water demand used in measuring conservation.

The second item relates to how the irrigator maximizes profits. It is assumed that the irrigator produces crops through a two-stage budgeting process. This means the irrigator does not allocate all inputs simultaneously, but rather allocates inputs in two-steps. In the first stage (at the extensive margin and at the beginning of the growing season), the irrigator allocates acreage. At the extensive margin, the profit maximizing irrigator will allocate acreage based on the expectation of the water needs and output from each crop such that:

6) $$E\left\{p_k \frac{\partial f(\bullet)}{\partial EW_k(\bullet)} \frac{\partial AW_k(\bullet)}{\partial l_k} d\right\} \leq E\left\{r \frac{\partial AW_k(\bullet)}{\partial l_k} + h\right\}$$

Now recall that in equation 1) applied water was defined as a function of acreage allocations. In the second stage (at the intensive margin and after acreage is allocated), the irrigator will apply water to the crops such that:

$$7) \qquad E\left\{ p_k \frac{\partial f(\bullet)}{\partial EW_k(\bullet)} d \right\} \leq r$$

where the marginal revenues from production are at least as great as the marginal costs of water.

The general interpretation of equations 6) and 7) is quite simple. Equation 6) states that irrigators will allocate acreage until the expected revenues of that acreage are at least as great as the expected water costs of that acreage. Equation 7) shows that once acreage is allocated, irrigators will apply water to that acreage such that the expected marginal revenue of that water is at least as much as the water costs.

The primary distinction between equations 6) and 7) is whether or not acreage is flexible. In equation 6), acreage is the lone choice variable, while in equation 7) acreage is already allocated and water applications given acreage allocations is the choice available to the irrigator. Consequently, equation 6) is the acreage allocation decision, and includes the acreage fees associated with water while equation 7) is the water allocation decision with acreage already allocated and acreage fees are a fixed cost. This has significant implications for evaluating the effects of water rate reform, and can be shown through differentiation of equations 6) and 7) with respect to h and r. Implicit differentiation of 6) and 7) shows how acreage allocations and water applications respond to changes in both prices. Note that irrigation technology is held constant in this example. This shows how changing the tariff structure faced by an irrigator changes water use at both the extensive and intensive margins. For $\frac{\partial l_k}{\partial h}$, the results are:

8) $$\frac{\partial l_k}{\partial h} \leq \frac{1}{\left(p_k \frac{\partial^2 f(\bullet)}{\partial EW_k^2} d^2 - r \right) \frac{\partial^2 AW_k}{\partial l_k^2}}$$

while for $\frac{\partial l_k}{\partial r}$ the results are:

9) $$\frac{\partial l_k}{\partial r} \leq \frac{\frac{\partial AW_k}{\partial l_k}}{\left(p_k \frac{\partial^2 f(\bullet)}{\partial EW_k^2} d^2 - r \right) \frac{\partial^2 AW_k}{\partial l_k^2}}$$

both equations 8) and 9) are less than zero due to standard restrictions on the production function.

The impacts of a change in the price of water at the intensive margin are somewhat different. Since acreage is already allocated, the acreage fee, *h*, does not influence actual water applications. As a result, the marginal effects of a change in the volumetric element of water costs, r, are:

10) $$\frac{\partial AW_k}{\partial r} \leq \frac{1}{p_k \frac{\partial^2 f(\bullet)}{\partial EW_k^2} d^2}$$

Equation 10) is also less than zero due to standard restrictions on the production function.

Comparison of equations 8), 9) and 10) shows that it is difficult to determine if acreage is more or less elastic than applied water. The comparative elasticities depend primarily on the functional relationship between applied water and acreage. However, empirical research suggests irrigators respond to drought and water scarcity more through fallowing than water-shorting (Sunding et al., 1997). This would indicate that equations 8) and 9) tend to be more elastic than equation 10).

The discussion now returns to equation 2). Taking equations 8), 9) and 10) and substituting them into equation 2) gives:

$$11)\qquad d\,AW = \sum_k \left(\frac{dr}{p_k \dfrac{\partial^2 f(\bullet)}{\partial EW_k^2} d^2} \right) dr + \sum_k \left(\frac{\dfrac{\partial AW_k}{\partial l_k}}{\left(p_k \dfrac{\partial^2 f(\bullet)}{\partial EW_k^2} d^2 - r \right) \dfrac{\partial^2 AW_k}{\partial l_k^2}} \left(\frac{\partial AW_k}{\partial l_k} dr + dh \right) \right)$$

With the information from equations 8) through 10) included, it is apparent that increasing either price in isolation will lead to a reduction in applied water. However, when one price rises while another falls, the effects are unclear. Empirical analysis is a necessity.

Empirical Model and Policy Implications

In response to USBR policy initiatives, the Arvin Edison Water Storage District ("the District") modified its water rate structure in 1995. Specifically, the District adopted a "cash and carry" system. Prior to 1995, irrigators contracted for a quantity of water with the District at the beginning of the growing season. Irrigators paid a per-acre fee for delivery of a specific quantity of water (the "standby" fee) at the beginning of the growing season and then paid a volumetric fee (the "delivery" fee) when and if the water was delivered. After 1995, the District reduced the "standby" fee and no longer required irrigators to contract for a specific quantity of water at the beginning of the growing season. Rather, irrigators simply request and pay for water when and as it is needed. To compensate for the reduction in the "standby" fee, the District increased the "delivery" fee.

This change was intended to be revenue-neutral and to leave on-farm water costs constant. Prior to 1995, the standby charge was $118.25/ac and the delivery charge was

$45.30/acre-foot[1]. After the rate change, they were $71/acre and $65.30/acre-foot respectively. An irrigator using 3.5 acre-feet per acre (the District average use) would have paid a total of $446.90/acre in water costs before the rate change and $469.65/acre in water costs after the rate change; the difference between the two costs is due to changes in fees paid by the District to the USBR.

The primary effect of the rate-change was to make acreage cheaper and water more expensive while keeping the District's revenues steady. As such, this is an example of a two-part tariff used to balance a budget. This is a primary use of two-part tariffs, and their use is well supported in utility pricing literature (Ng and Weissner, 1974). However, as the theoretical results indicate when the two elements of the tariff move simultaneously in opposite directions, it is impossible to determine what the effects on demand will be. This is exactly what the District did, and the consequences of the rate change are unclear. Since the District adopted the new rate structure, water deliveries to irrigators have oscillated from 137,000 acre-feet in 1994 to a high of 151,000 acre-feet in 1999 and a low of 111,000 acre-feet in 1998[2].

The success of the rate change in promoting water conservation is a major concern of the District. To analyze this issue empirically, alternative sets of acreage-based and volumetric water prices are applied to the District and simulated through mathematical programming. This is not a simple task. Stochasticity and hydrology greatly complicate analysis of the alternative prices in the District. Irrigators in the District face several sources of uncertainty in their production decisions. Water inflows and yields are both stochastic. Additionally, the District

[1] The District delivery charge varies with elevation and the number of pumping lifts needed to deliver water to a particular field. The volumetric charges are for the District-average of 2.6 pumping lifts.
[2] Surface inflows into the District were 251,000 acre-feet in 1999 and 214,000 acre-feet in 1998.

operates a conjunctive use system (joint use of surface water and ground water to stabilize water supplies). As a result, it is necessary to model not only the dynamics of the surface water system in the District, but also the related ground water dynamics.

Conventional analysis of this problem would use dynamic stochastic programming. However, this generally requires significant simplification of the District's hydrology and of the choices facing individual irrigators. An alternative approach is a discrete time non-linear programming model with chance constraints (Standiford and Howitt, 1992). This approach allows for greater precision in modeling the District's hydrology while still capturing uncertainty in yields and water supplies.

Using field-level crop acreage data for the 1997-1998 water year for the 10 primary crop groups in the District, a chance-constrained non-linear programming model was developed to simulate irrigator responses to changes in all fees related to water from the District. The District typically sets prices in 3-year increments and the model simulates responses across a 3-year management horizon. The District uses the following crop categories in its record keeping: field (almost entirely cotton), grain, pasture (almost exclusively alfalfa), truck, citrus (mostly oranges), deciduous (predominantly almonds), and vine (mostly table grapes). Carrots, potatoes, and onions are all counted in the 'truck' category, but were given their own categories in this research because of both their prevalence and their distinctly different water requirements. The remaining 'truck' crops are primarily tomatoes and peppers. Additionally, since fallowing is generally a short-run response to water shortage and establishing perennial crops typically takes longer than 3 years, it was assumed perennials like citrus, deciduous, and vine crops will not be taken out of production in the short run.

Reported crop acreage was taken from the District annual crop reports and represent total acreage for spring cropping. Water costs were taken from District records. Crop prices and yields were taken from the Kern County Agricultural Commission while production costs came from the University of California Extension Service (Kern County Agricultural Commission, 1997; UC Extension Service). This data is summarized in Table 1.

The model is programmed in the Generalized Algebraic Modeling System to determine optimal water usage as both the volumetric and acreage-based elements of water price vary. The model is calibrated to existing cropping patterns through Positive Mathematical Programming (Howitt, 1995). Chance constraints are added to reflect stochasticity in crop yields and corresponding water requirements (Charnes and Cooper, 1959).

The results from the simulation models are summarized in Figures 1 and 2. Figure 1 shows surface water applications across alternative surface water prices and acreage charges in the District's Surface Water Service Area[3]. As Figure 1 shows, water applications decline noticeably in the District's volumetric price and slightly in the District's acreage-based fee (the 'standby' charge). While the reduction in water applications across both prices suggests that adjustments in water tariffs can promote water conservation, the fact the surface of Figure 1 is not level suggests that it is possible to move the two elements of water price in directions that send conflicting conservation signals to irrigators. Additionally, it is also important to realize that nearly half of all District acreage is in 'perennial' crops (citrus, deciduous and vine) that are not fallowed in the short run. Consequently, while some of the reductions in water applications stem from adjustments in water application rates, most of it occurs from fallowing.

This is shown in Figure 2, which maps out adjustments in 'annual' acreage crops across both the acreage-based and volumetric water prices. The acreage allocation surface in Figure 2

[3] The District is divided into 2 regions, the Surface Water Service Area (SWSA) and the Ground Water Service Area (GWSA). Irrigators in the SWSA can receive water deliveries from the District and may also have on-farm access to ground water. Irrigators in the GWSA cannot receive surface water from the District and must rely on ground water. Since the District's pricing policies only affect irrigators in the SWSA, the present analysis focuses solely on the SWSA.

shows that most of the changes in water applications seen in Figure 1 stem from fallowing of 'annual' crop acreage. While this result is consistent with existing research that identifies fallowing as a primary response to water scarcity (Sunding et al., 1997), it raises serious questions about the production effects of water price reforms.

Another implication from the shape of the acreage allocation surface in Figure 2 is that changes in the volumetric price of water do not influence all acreage equally. While changes in the acreage-based component of water price are applied to all acreage in a uniform manner without respect to the crop planted, the effects of changes in the volumetric component of water affects each crop differently. Since each crop has different water requirements, changes in the price of water will have a relatively greater impact on some crops than others, and can potentially alter the relative profitability of each crop. Additionally, since so much of the District's acreage is in perennial crops that are essentially permanent, changes in the price of water tend to be a tax that is simply absorbed by these irrigators while most reductions in water usage come from acreage reductions by annual crops. The end result is that most of the water conservation burden is carried by the producers of non-perennial crops.

Summary and Conclusions

Recent policy proposals introduced by the USBR promote adoption of conservation pricing systems by irrigation districts receiving federal water. Most analysis of conservation pricing centers on volumetric water prices while most irrigation districts use either acreage-based water fees or a combination of acreage-based and volumetric water fees. The present analysis recognizes that the use of a combined acreage-based and volumetric water pricing system implies that an irrigation district is actually using a two-part tariff pricing system rather than the single-part tariff implied by most conservation pricing research.

Simultaneous changes in the two elements of a two-part water tariff can send mixed conservation signals to irrigators. This is because the water price is being levied on two inputs (water and land), not simply one (water). Theoretical indicate that while water applications are generally declining in both the volumetric price of water and the related acreage-based fees, it is possible to move the two parts of the water tariff in directions that send mixed conservation signals. Simulation through dynamic optimization confirms these theoretical results. Additionally, simulation results show that changes in the volumetric water price generally do not have uniform effects across different crops. Differences in the water requirements across crops mean that while the acreage-based fees exert a uniform impact across all crops, the volumetric price does not. This results in acreage levels being much more sensitive to changes in the volumetric price than the acreage-based fee.

Overall the results suggest changes in the price of irrigation water, whether through adjustments in acreage-based or volumetric fees, can reduce water usage. However, the consequences of those changes will depend heavily upon which price is changed and what crops are grown in a region. Consequently, while water pricing can be a valuable conservation tool, its effectiveness depends strongly on how irrigators are charged for their water. The form of the water price and how price changes are implemented are both critical issues when analyzing conservation pricing programs.

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Table 1: Summary Statistics

	Price	*Yield per Acre*	*Water Use per Acre*	*District Acreage*	*Units*
Alfalfa	91.40	7.97	3.96	3331	Tons
Carrots	152.94	24.94	1.27	2661	Tons
Cotton	0.73	1182.60	2.57	13710	Pounds Lint
Onions	71.95	19.45	2.31	3735	Tons
Potatoes	180.45	18.68	1.73	15994	Tons
Grain	115.94	2.45	1.87	4851	Tons
Truck	165.97	17.45	2.14	6106	Tons
Citrus	337.48	13.09	2.80	11811	Tons
Deciduous	1269.03	1.83	3.50	11609	Tons
Vine	440.37	8.12	2.30	28086	Tons
Fallow				10544	

NOTE: Prices and yields are taken from Kern County Agricultural Commission Annual Reports, 1989-1998. Water-use is the ET and leaching requirements by crop per acre and is taken from District crop water use reports prepared by the firm of JMLord. They are also the average from 1989-1998. Acreage is spring cropping for the 1997/1998 water year in the District and is taken from District records.

Figure 1: Surface Water Use in the Surface Water Service Area (SWSA)

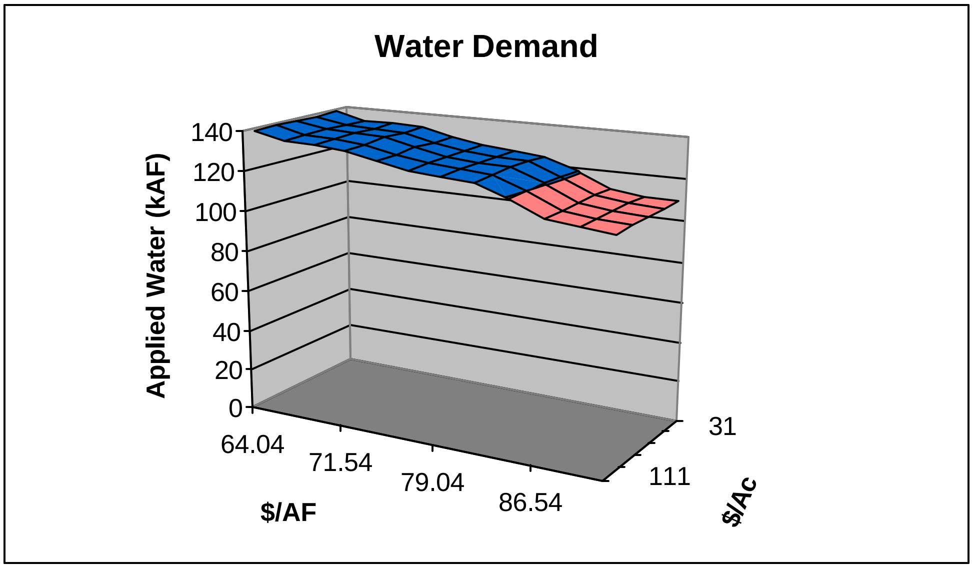

Figure 2: Annual Acreage Levels in the Surface Water Service Area (SWSA)

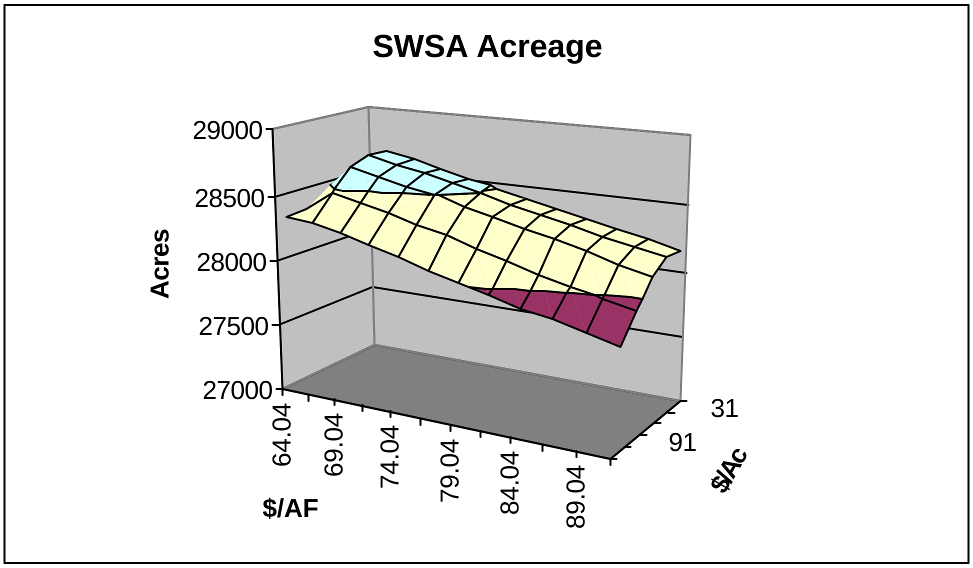

Figure 3: Aquifer Drawdown