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Evaluating the Effectiveness of Conservation Water-Pricing Programs

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Charging farmers increasing block prices for irrigation deliveries is advocated as a means of encouraging agricultural water conservation in the West. We formulate a model of a hypothetical irrigated river basin to investigate the hydro-economic circumstances in which such pricing leads to water conservation. Our results indicate that increasing delivery prices may encourage irrigators to make adjustments with countervailing impacts on consumptive water use and conservation. Whether these countervailing impacts combine to conserve water or increase its consumptive use must be resolved empirically. An alternative resolution of this ambiguity is to assess water prices in terms of consumptive use.

Key words: irrigation efficiency, water conservation, water pricing

Introduction

The presumption that increasing block water prices encourage agricultural water conservation is firmly entrenched in much of western water policy (U.S. Bureau of Reclamation; Willey and Diamant). We formulate a hydro-economic model of a hypothetical irrigated river basin to test this presumption under a variety of hydrologic circumstances.

Water Demand Management

The era of expanding increasingly contested water supplies in the western United States via large-scale and federally subsidized water development projects has ended. Principal reasons are political opposition to enlarged budget deficits and environmental opposition to adverse ecological impacts associated with the operation of water collection, storage, and transportation facilities (Gould). Consequently, irrigation districts receiving federally subsidized water are under increasing pressure from the federal government to engage in "water demand management" to conserve water used in agriculture. Water demand management refers to "the integrated use of conservation practices and pricing to influence water use—both the total level of water use and the pattern of use" (U.S.

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Bureau of Reclamation, p. 10). Western states such as Washington also are investigating the use of water demand management to encourage agricultural water conservation by state irrigation districts (Willey and Diamant).

Willey and Diamant, co-authors of an Environmental Defense Fund water conservation study commissioned by the state of Washington, developed the tiered pricing model reproduced in figure 1 to demonstrate how water demand management purportedly leads to water savings in irrigated agriculture. The pricing structure charges increasing block prices for water delivered and applied to crops. Such tiered pricing structures are becoming increasingly common in the West (Michelsen et al.). Irrigation districts in the Central Valley of California are required by the Central Valley Project Improvement Act to adopt water conservation plans including tiered pricing structures,[1] and the federal government encourages districts in other areas to do so (U.S. Bureau of Reclamation).

The first tier in figure 1 prices water deliveries from an irrigation district to an irrigator at point P(1), which is in units of dollars per acre-foot of water ($/AF). The first tier covers deliveries up to tiering level T(1), which is in units of acre-feet per acre (AF/A). The first tier price can be set to ensure that water delivery costs are recovered if farmers complete seasonal irrigations with first tier water only. The second tier is priced somewhat higher at P(2), and covers water deliveries between tiering levels T(1) and T(2). Finally, the third tier is priced yet higher at P(3), and covers water deliveries beyond T(2). Willey and Diamant assume that the third tier price is set to equate the irrigator's marginal value product of delivered water in irrigation to the district's marginal supply cost to encourage economically efficient water applications.

Based on their investigation, Willey and Diamant contend that the tiered pricing structure in figure 1 leads to agricultural water conservation in the following way: Let P(1) represent traditional "flat rate" pricing water deliveries in a single block at a relatively low rate. Each irrigator in the district demands a water delivery of Q(1). If the district subsequently adopts the tiered pricing scheme in figure 1, then each irrigator is assessed P(3) for the tier including the previous demanded delivery, Q(1). The increased water price encourages each irrigator to reduce his/her demand for water deliveries to the economically efficient level, Q(3). The difference, Q(1) - Q(3), is referred to as a "tier-induced reduction," and is presumed to measure water savings (p. 80). The authors conclude that "[the effectiveness of tiered prices] in reducing water consumption depends on how sensitive the users are to price increases—in other words, on the price elasticity of demand" (Willey and Diamant, Executive Summary, p. iii). In summary, increasing block water prices encourage each farm to reduce its demand for delivered water to an extent which depends on its price elasticity of demand, and the tier-induced reduction is presumed to constitute water savings.

In the following section, we formulate a hydro-economic model of a hypothetical irrigated river basin to demonstrate how this common presumption of tier-induced water conservation is oversimpified. The presumption of conservation disregards the countervailing water supply impacts of adjustments in on-farm irrigation efficiencies that farmers also have been observed to make in response to increasing block water rates (Wichelns; Wichelns and Cone).

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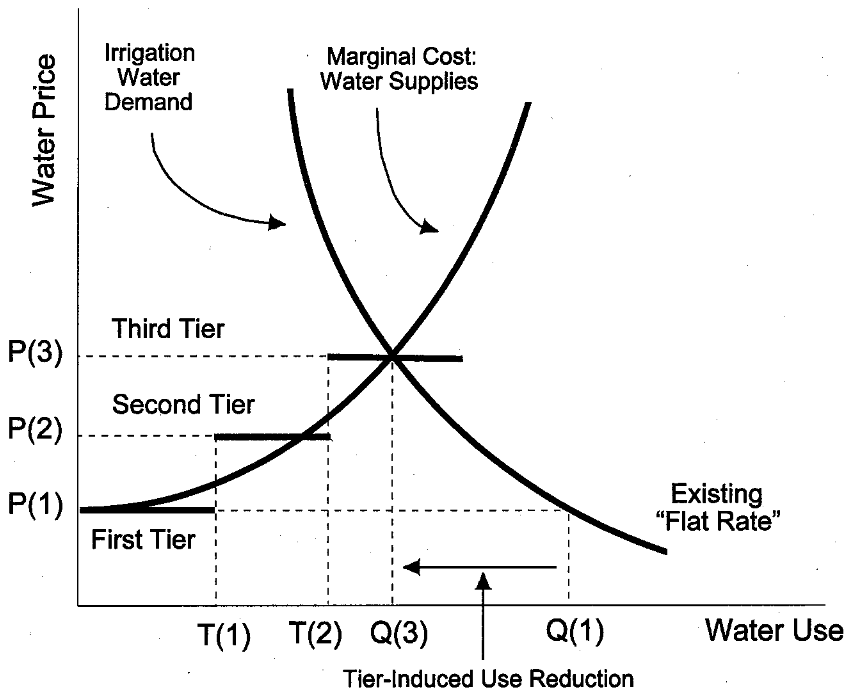
[1] 43 U.S.C. § 390jj(b).



Source: Willey and Diamant (fig. 24).

Figure 1. Marginal cost-based tiered water pricing

A Hypothetical Irrigated River Basin Model

Consider a single irrigation district delivering water over a fixed irrigation season to equally productive farms located along a river of constant depth and within a basin of constant width. Each farm produces the same single crop with an identical on-farm irrigation efficiency, E, determining the fraction of delivered water consumed in crop production, C (AF/A), according to:

(1) $$C = EQ,$$

where $0 \leq E \leq 1$, and Q (AF/A) continues to represent delivered water (Whittlesey, McNeal, and Obersinner).

Since on-farm irrigation efficiency is typically less than 100%, crop production depends on consumptive water use C, and not solely on water deliveries Q as in figure 1 (Chakravorty, Hochman, and Zilberman). The crop production function, $Y = F(C)$, is characterized by a positive and decreasing marginal product, i.e., $F_C > 0$, and $F_{CC} < 0$. Consequently, each profit-maximizing farm faces a derived demand for consumptive water use of:

(2) $$P_Y F_C(C) = P,$$

where P_Y is the unit price of the crop, and P continues to represent the cost of delivered water.

To model the impact of irrigation deliveries and consumptive use on the quantity of water in the river at a given location, we modify a volumetric stream flow equation found in the literature (Chakravorty, Hochman, and Zilberman) by introducing the possibility of irrigation return flows. Let x represent the distance from the point at which water initially flows into the river basin ($x = 0$) to a point at which the irrigation district delivers water to a given farm. In addition, let W_x represent the level of instream flows at distance marker x for a fixed irrigation season. Then the spatial rate of change in the quantity of instream flows at x is given by:

$$(3) \qquad W'(x) = -Q_x\alpha + \delta(Q_x - C_x)\alpha,$$

where $W'(x)$ is in units of acre-feet of water per unit distance x, and α measures the constant width of the irrigated river basin. The parameter $0 \leq \delta \leq 1$ is set to reflect a range of exogenous hydrologic conditions. If $\delta = 0$, then the difference between water application and consumptive water use is irretrievably lost to the river basin (i.e., as in an "open" hydrologic system). If $\delta = 1$, then the difference returns to the river as an irrigation return flow (i.e., as in a "closed" hydrologic system). Finally, a value of δ between 0 and 1 represents a range of intermediate cases in which the difference between water application and consumptive use is split between irretrievable losses (e.g., evaporative losses) and return flow. The first term on the right-hand side of equation (3) subtracts the quantity of irrigation water applied over the width of the river basin at x, and the second term adds any irrigation return flows back into the river ($\delta > 0$).

Differential equation (3) can be solved for the quantity of instream flows at x for fixed values of irrigation deliveries, on-farm irrigation efficiency, and consumptive use. These fixed values arise as each farm responds to a fixed water delivery price P_f. Each farm determines its profit-maximizing level of consumptive water use (C_f) according to equation (2), and the required water delivery (Q_f) using equation (1) for a given level of on-farm irrigation efficiency (E_f). Inserting these fixed values into equation (3) and solving for the level of instream flows at x yields:

$$(4) \qquad W(x) = W_0 - Q_f\alpha x + \delta(Q_f - C_f)\alpha x,$$

where $W(x)$ is in units of acre-feet of water. The quantity of instream flows at x is given by the difference between basin inflows at the origin, $W(0)$, and accumulated water deliveries applied over the width of the basin up to x (the second right-hand-side term). If $0 < \delta \leq 1$, then instream flows are augmented by the accumulated irrigation return flows up to x (the third right-hand-side term).

Model Analysis

We now analyze the hydro-economic model defined by equations (1), (2), and (4) to investigate whether increased water prices lead to agricultural water savings under a range of hydrologic circumstances prevailing in the West. We implicitly differentiate each equation with respect to the water rate P, and evaluate the derivatives at a status quo flat water price of $P_f = P_1$. Forward substitution is used to solve for $\partial W(x)/\partial P$, which summarizes whether instream flows increase or decrease after each farm has adjusted optimally to an incremental increase in water rates from P_1. A positive (negative) value for $\partial W(x)/\partial P$ indicates that farmer adjustments to an increased water price result (do not result) in water conservation.

The derivative of consumptive use equation (1) with respect to P is:

$$\frac{\partial C}{\partial P} = E(P_1)\frac{\partial Q}{\partial P} + Q(P_1)\frac{\partial E}{\partial P}, \tag{5}$$

where the marginal change in on-farm irrigation efficiency with respect to the water price is assumed to be positive, i.e., $\partial E/\partial P > 0$. This restriction is consistent with the expectations of water administrators in recommending tiered water pricing: "The primary goal for irrigation districts embracing water demand management is to get farmers to increase their water use efficiencies to assure supplies for other purposes or future needs" (U.S. Bureau of Reclamation, p. 10). It is also consistent with the available empirical evidence. For example, farmers in California's Broadview Water District increased their on-farm irrigation efficiencies in response to increasing block prices for delivered water with "shortened furrow lengths, reduced set times, and alternate-furrow application during some irrigations" (Wichelns, p. 288).

Equation (5) can be reexpressed conveniently in elasticity form as:

$$\frac{\partial C}{\partial P} = \frac{C(P_1)}{P_1}(\varepsilon_{Q,P} + \varepsilon_{E,P}), \tag{6}$$

where $\varepsilon_{Q,P} = (P/Q)\partial Q/\partial P$ is the price elasticity of demand for water deliveries, and $\varepsilon_{E,P} = (P/E)\partial E/\partial P > 0$ is the elasticity of demand for investment in improved on-farm irrigation efficiency with respect to the water price (referred to below as the "price elasticity of irrigation efficiency").

The derivative of demand equation (2) with respect to P is:

$$P_Y F_{CC}\frac{\partial C}{\partial P} = 1, \tag{7}$$

or after substituting in equation (6):

$$\frac{P_Y F_{CC} C(P_1)}{P_1}(\varepsilon_{Q,P} + \varepsilon_{E,P}) = 1. \tag{8}$$

Solving for the price elasticity of delivered water ($\varepsilon_{Q,P}$) in equation (8) yields:

$$\varepsilon_{Q,P} = \frac{P_1}{P_Y F_{CC} C(P_1)} - \varepsilon_{E,P} < 0, \tag{9}$$

which is negative because $F_{CC} < 0$, and $\varepsilon_{E,P} > 0$ by assumption.

Finally, the derivative of volumetric instream flow equation (4) with respect to P can be shown to be:

$$\frac{\partial W_x}{\partial P} = \left[(1-\delta)\frac{Q(P_1)}{P_1} + \delta\frac{C(P_1)}{P_1}\right]|\varepsilon_{Q,P}|\alpha x - \delta\frac{C(P_1)}{P_1}\varepsilon_{E,P}\alpha x. \tag{10}$$

In the absence of irrigation return flows ($\delta = 0$), equation (10) collapses to:

$$\frac{\partial W_x}{\partial P} = \frac{Q(P_1)}{P_1}|\varepsilon_{Q,P}|\alpha x > 0. \tag{11}$$

Water delivered from the river and applied to crops is forever lost to the river. Hence, a price-induced reduction in demanded water deliveries increases instream flows, and constitutes water savings that increase at a rate proportional to the price elasticity of demand for delivered water.

In the absence of irretrievable water losses ($\delta = 1$), equation (10) collapses to:

$$\frac{\partial W_x}{\partial P} = \frac{C(P_1)}{P_1}\left(|\varepsilon_{Q,P}| - \varepsilon_{E,P}\right)\alpha x, \tag{12}$$

which is negative for $\varepsilon_{E,P} > |\varepsilon_{Q,P}|$, positive for $\varepsilon_{E,P} < |\varepsilon_{Q,P}|$, and zero for $\varepsilon_{E,P} = |\varepsilon_{Q,P}|$. Because the portion of water deliveries unconsumed in crop production returns to the river, water loss only occurs through consumptive use. Thus, the rate at which instream flows change in response to an increased water rate is inversely related to the response of consumptive water use. Consumptive use increases (and instream flows decrease) in response to a price increase when the price elasticity of delivered water is less in absolute value than the price elasticity of irrigation efficiency. Alternatively, consumptive water use decreases (and instream flows increase) when the inequality holds in the opposite direction. Consumptive use and instream flows remain at constant levels when the elasticities are offsetting.

Finally, if the difference between water application and consumptive use is split between irretrievable losses and irrigation return flows ($0 < \delta < 1$), then a price-induced reduction in demanded water deliveries is increasingly apt to result in greater instream flows as the proportion of irretrievable water losses increases (i.e., as $\delta \to 0$) by equation (10).

Discussion

As described above, the water policy literature commonly presumes that increased prices for delivered water lead to agricultural water savings at levels directly related to the price elasticity of delivered water. Our analysis demonstrates that this presumption is indisputable only for the polar case in which the portion of water deliveries unconsumed by crops is irretrievably lost to the river basin. In the absence of irrigation return flows, instream flows are reduced by the amount of water delivered from the river to the farm, and this reduction depends on the farmer's price elasticity for delivered water.

In reality, irrigation return flows constitute a significant component of instream flows in the West (see, e.g., Hydrosphere Resource Consultants). In the presence of irrigation return flows, instream flows decrease by the portion of the delivery that is consumptively used and irretrievably lost, and this significantly complicates the linkage between delivered water rates and conservation. Consumptive water use is directly related to both the demanded water delivery and on-farm irrigation efficiency, but increased water prices have opposite impacts on these two components. As prices increase, the farmer reduces the demand for delivered water according to the price elasticity of water delivery (depressing consumptive use), but increases the portion of the delivery consumed in crop production by improving on-farm irrigation efficiency according to the price elasticity of irrigation efficiency. Whether these countervailing impacts combine to reduce consumptive water use and increase instream flows is an empirical question depending on the relative magnitudes of the two elasticities.

In sum, the common presumption linking increased water rates to water conservation as a function only of the price elasticity of delivered water is unrealistic for general western hydrologic conditions and, as a consequence, is overly simplistic. It can give rise to a false expectation of water conservation in the presence of return flows when, in the worst-case scenario, consumptive water use actually increases if the price elasticity of irrigation efficiency predominates over the price elasticity of delivered water. Under these circumstances, water demand management backfires and exerts more pressure on scarce water supplies.

Should irrigation districts continue to adopt tiered pricing structures based on delivery quantities despite the possibility that such structures may generate false expectations of water conservation or, worse yet, exacerbate scarcity? Irrigation districts base their water rates on water deliveries because measuring and monitoring a farm's consumptive use is generally more costly (Gould). The opportunity cost of achieving this cost efficiency in conservation pricing schemes is that the impacts of increased delivery rates on consumptive water use and conservation may be ambiguous, and these ambiguities can only be resolved empirically. Alternatively, the benefit of incurring the increased costs of pricing water according to consumptive use is that farmers are expected to unambiguously reduce water consumption, which is often the major means of generating water savings in western hydrologic systems. In short, irrigation districts must weigh increased measurement and monitoring costs against the public pressure to guarantee true agricultural water savings in determining whether to shift pricing to a consumptive use basis.

Conclusion

Increasing block water prices for delivered water are commonly presumed to lead to agricultural water conservation in amounts depending on the price elasticity of demand. Our analysis demonstrates that this presumption is overly simplistic for the irrigation return flow hydrologic systems characterizing the West. Under return flow conditions, increasing block prices encourage farms to reduce demanded irrigation deliveries, but also increase the efficiency with which the reduced deliveries are consumed in crop production. These adjustments have countervailing impacts on agricultural water conservation, and thus transform the commonly presumed theoretical certainty of water savings from increased water prices to an empirical uncertainty. This uncertainty can be resolved by assessing water price in terms of consumptive water use instead of water deliveries. However, assuming that irrigation districts will continue to price water based on delivery, agricultural economists can aid public policy makers in predicting the water conservation potential of tiered pricing schemes in a given region by producing empirical estimates of the price elasticities regulating the above countervailing adjustments.

On a final note, we should recognize that tiered water pricing is used for purposes other than water conservation. For example, it is used successfully in California's Broadview Water District to encourage farmers to reduce toxic irrigation return flows as part of a regional plan for implementing state water quality guidelines (Wichelns; Wichelns and Cone). This is consistent with our analysis because, although the aforementioned farm adjustments to increasing water prices have countervailing impacts on water conservation, they act in concert to reduce irrigation return flows. The implication for water policy is that tiered water pricing may trigger a tradeoff of water quality for water quantity benefits which must be recognized and managed optimally to ensure regionwide economically efficient water management.

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