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# Determining the Price-Responsiveness of Demands for Irrigation Water Deliveries versus Consumptive Use

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A water-crop simulation/mathematical programming model of irrigation water demand in northeastern Colorado is formulated to develop an original concept of derived demand for consumptive use of water. Conventional demand functions for water deliveries are also developed, and the effect of hypothetical price increases on both consumption and delivery are illustrated. Findings indicate that demand elasticity estimates are quite sensitive to model specification, and consumptive use demand tends to be significantly less price-responsive than delivery demand. Thus price incentives are likely to have only limited impacts on basin-wide water consumption and would not make much additional water available for emerging demands.

*Key words:* crop simulation, irrigation, mathematical programming, water conservation, water-demand elasticities, water policy

## Introduction

Irrigation of agricultural crops accounts for 80% to 90% of water withdrawals in the semi-arid and arid western United States. Much of the water used for irrigation yields relatively low net returns, so initiatives to meet growing urban and environmental demands by using price incentives are increasingly being discussed and in some cases put into effect.

Under the prior appropriation water law doctrine prevalent in the western United States, which relies on the legal ownership of water rights, farmers usually do not pay for irrigation water per se. Rather, they are charged for (some of) the costs of capturing and transporting the water to their farms as well as the operational costs of the irrigation company or district servicing them. However, since the beginning of the 1990s, efforts have been made at both the state and federal levels to encourage agricultural water conservation using a range of measures including water pricing. One example is the Central Valley Project Improvement Act passed by Congress in 1992 that introduced a tiered pricing schedule to be implemented at the irrigation district level (Weinberg, 1997). Another example is the policy adopted in 1996 by the Bureau of Reclamation of the U.S. Department of the Interior which encourages and, in some cases, requires irrigation districts receiving federal reclamation water to incorporate conservation price

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incentives as part of their conservation plans (Michelsen et al., 1999). A detailed handbook was prepared in 1997 to help agricultural water districts and irrigation organizations develop price incentives to achieve more efficient water use throughout the western United States (U.S. Department of the Interior, 1997).

In a river basin context, when analyzing competing water demands involving the agricultural sector, it is useful to distinguish among three measures of water use: water withdrawals, deliveries, and consumptive use. Withdrawal measures the amount of water diverted from the surface or ground water source. Delivery refers to the amount of water delivered to the place of use, i.e., the farm. Withdrawal minus conveyance losses equals delivery. Consumptive use is the amount of water that is actually depleted—lost to the atmosphere from evaporation and transpiration from plant and soil surfaces, and embodied in plant products.

In field irrigation situations, delivery exceeds consumptive use for several reasons, mainly because of on-farm transit losses and field losses due to the imprecision of the water application practices. For example, in the case of irrigation with open ditch with siphons, in order to assure sufficient water reaches plants at the end of the field, an excess is applied at the beginning. Farmers also may not know the precise amount of irrigation water needed and apply more water than strictly necessary. Furthermore, in some areas, water in excess of consumptive use may be applied to carry salts below the crop root zone. The difference between withdrawals and consumptive use is called return flow. With consumptive use typically amounting to 40% to 60% of deliveries, return flows represent a relatively large portion of deliveries, and in many river basins constitute an important part of the downstream water supply.

Water economists have long recognized the importance of considering the different measures of water use in their analyses (Hirschleifer, De Haven, and Milliman, 1960, p. 69; Hartman and Seastone, 1965, p. 167). Bain, Caves, and Margolis (1966) draw attention to the problem "of placing any emphasis on gross, rather than net, demands for water, since the over-all adequacy of water supplies depends on the net consumption occurring in any given use" (p. 16). Nevertheless, most research on irrigation water demand and its price-responsiveness has concentrated on delivery demands and paid little attention to consumptive use demands. This focus is not surprising because delivery is usually the farmers' decision variable, and information on the consumptive use of irrigated crops (and, for that matter, return flows) has not readily been obtained. However, in light of increasing competition between water demands, water policy initiatives such as volumetric charges for irrigation water need to be examined not only with regard to their effect on deliveries, but also on consumptive use and return flows. Although price incentives involving higher costs of irrigation water may change producers' requests for water deliveries, we expect that the amount of water consumed would be relatively less affected. This analysis develops and implements an approach to measuring the relative effects of hypothesized price incentives on deliveries and consumption of irrigation water.

While analyses of the demand for irrigation water use have appeared in the literature since the early 1960s, the elasticity estimates and related policy recommendations differ widely. Some researchers found that farmers are very unresponsive to changes in the price of water. Therefore, they commonly caution against the use of pricing policy to bring about reductions in deliveries, because even for relatively small reductions, large price increases would be necessary—with significant effects on agricultural income and wealth.

Other studies indicate a more elastic demand, and their authors conclude that pricing policy would be an effective instrument since it would provide the necessary incentives for farmers to adjust to rising prices by using irrigation water more efficiently. Despite the importance of knowing the responsiveness of farmers to price changes, little systematic study has been carried out on the factors which cause these differing findings.

Several recent papers have used models incorporating water deliveries (or withdrawals) and consumptive use to show that for river basin planning purposes the responsiveness of consumptive use to policy initiatives is often equally or more relevant than is responsiveness of deliveries (or withdrawals). With a focus on the western United States, these studies examine the impact of a number of policy measures such as improved on-farm irrigation efficiency, limits on deliveries, and increases in delivery prices. Using a numerical example, Huffaker and Whittlesey (1995) illustrate that improvements in on-farm irrigation efficiency appear to conserve water by reducing withdrawals, but in reality redistribute water between river and aquifer and do not necessarily change consumptive use. Focusing on the impacts of limits in agricultural water deliveries, Bernardo et al. (1987) use a farm-level crop simulation/mathematical programming model to show that through better-timed irrigations large decreases in delivery demands may be attained with only marginal reductions in consumptive use and crop yields. Similarly, Burke et al. (2001) explore the effectiveness of limiting deliveries with the goal of conserving water for alternative uses. By linking an on-farm economic decision model with a basin-wide hydrologic model of return flow, they demonstrate that when substitution of technology for water supply is allowed for (in addition to crop switching and land fallowing), the resulting decrease in consumptive use is considerably less than the reduction in deliveries.

Huffaker et al. (1998) analyze the impact of price changes for irrigation deliveries on agricultural water conservation based on theoretical derivations. According to their findings, the common presumption that increasing prices for deliveries leads to agricultural water conservation at levels directly related to the price elasticity of delivery demand is valid only where water unconsumed by crops is irretrievably lost to the river basin. In that special case, instream flows are reduced by the amount of water applied, and the reduction depends on the price elasticity of delivery demand. However, in the presence of return flows, instream flows decrease by the proportion of water applied which is consumptively used. Farmers would be encouraged by increasing block rates to reduce deliveries but, as improved irrigation technologies are adopted, they would also increase the efficiency with which the reduced deliveries are consumed in crop production. Thus the impact on instream flows is empirically uncertain. Huffaker et al. conclude this uncertainty can only be resolved by assessing water price in terms of consumptive use instead of water delivery.

The model we develop aims to address this issue raised by Huffaker et al. (1998) (and by Bain, Caves, and Margolis more than three decades earlier) by empirically analyzing the effect of hypothetical price increases for irrigation water on both the demand for deliveries and the derived demand for consumptive use. Our estimates are based on a two-stage water-crop simulation/linear programming model that was applied to the New Cache La Poudre Irrigation Company (NCLPIC), one of the dozen or so major irrigator-owned cooperatives in the lower South Platte Basin near Greeley, Colorado. Flows from the South Platte River and its tributaries serve the major urban-industrial centers and the most important agricultural region of Colorado. Over 80% of the water withdrawals from the South Platte are used for irrigation.

A linear programming model was chosen to estimate delivery and consumptive use demands since it can be easily adapted to represent numerous options available to farmers for adjusting to increased water prices (Paris, 1991). To carefully reflect the yield effects of reduced deliveries, the linear programming model incorporates water-crop production functions computed with a transient-state crop simulation model. An innovative feature of the water-crop production functions used in this analysis is that they show yield and consumptive use not only as a function of the amount of water applied during the season, but also as a function of the number and timing of irrigation events. This allows us to estimate the responsiveness of both deliveries and consumptive use to price changes under a wide range of adjustment options, including changes in irrigated acreage, cropping mix, irrigation technology, and irrigation scheduling.

Based on the model findings, we estimate the price-responsiveness of the demand for deliveries and the derived demand for consumptive use as well as the effect on net farm income, and discuss resulting policy considerations. The quantitative estimates of price elasticities of consumptive use demand are, to the best of our knowledge, the first in the literature to date. A comparison between the price elasticities of delivery and consumptive use demands reveals that consumptive use demand tends to be significantly less responsive to increased water price than delivery demand. This finding implies that price incentives for deliveries are likely to have only limited impacts on basin-wide water consumption and would not make much additional water available for competing demands.

We also examine the influence of different model assumptions regarding the substitutability of other resources for water on the estimated elasticities, and find that both delivery and consumptive use demand elasticities are quite sensitive to model specification.

## Previous Analyses of Price-Responsiveness of Deliveries

Estimates of the shape of the delivery demand function are commonly based on the use of mathematical programming models, especially linear programming models. Gardner (1983) presents an overview of the studies carried out in California during the 1960s and 1970s. The early studies often intended to show that the delivery demand is more price-responsive than generally believed, and that even for very low prices it is not perfectly inelastic as the U.S. Bureau of Reclamation had claimed in the past (e.g., Moore and Hedges, 1963). Later studies have constructed subregional or regional demand functions from models of representative farms, and commonly calculated responsiveness by either arc-elasticity estimates along the stepped demand curve or by fitting continuous regression equations to the parametric data. The results typically report either an inelastic estimate for the whole price range considered, or an inelastic estimate for the lower prices and a less inelastic or elastic estimate for the higher prices. The shape of the demand function may be influenced by various factors considered in the model such as the quality of the soil (Hedges, 1977), the length of the furrow (Yaron, 1967), the distinction between surface and groundwater (Hooker and Alexander, 1998), the product price (Gardner and Young, 1984), and the elasticity of the product demand curve (Howitt, Watson, and Adams, 1980).

During the 1970s and early 1980s, estimates of delivery demands and their shape have been developed with statistical crop-water production functions based on data from field experiments conducted at state experiment stations (Hexem and Heady, 1978; Kelley and Ayer, 1982). These analyses suggest optimal water applications per acre are very unresponsive to changes in price. A reason for this finding is that, while allowing changes in water applications for each of a few selected crops, these studies did not permit shifts in the cropping pattern or provide possibilities for substituting other inputs (e.g., labor or fertilizer) or alternative water application technologies for water.

More recently, econometric studies have used secondary data reflecting actual farmer behavior (Nieswiadomy, 1985; Ogg and Gollehon, 1989; Moore, Gollehon, and Carey, 1994). Their estimates tend to be more inelastic than suggested by the mathematical programming models, reflecting, at least in part, the differing assumptions and limitations of the two model types. Econometric models produce positive estimates based on historical data which often show little fluctuation in water prices, while mathematical programming models produce normative estimates based on both historical and synthetic data. The latter can be adapted to represent a wide range of scenarios, and model the impacts of policies for which no historical observations need to exist.

Overall, elasticity estimates vary widely—not only between model types, but also among mathematical programming models. Hartman and Whittlesey (1961), in an early study based on representative farms in Colorado, already noted that in addition to factors such as input and output prices, the kinds of adjustments farmers are allowed to make in the model in response to changes in water supply determine the value of additional water, and thus the shape of the demand curve. Our analysis builds on these findings and explores in more detail the effects of model formulation on the shape of both the delivery demand curve and the consumptive use demand curve.

## Modeling Procedure

The model developed here to measure price-responsiveness of demand for deliveries and consumptive use consists of two parts, an agronomic and an economic model. The data are based on the irrigation practices of NCLPIC in Weld County, Colorado. NCLPIC has relatively senior water rights for river flow, but reservoir water and groundwater from the unconfined shallow alluvial aquifer along the South Platte River are also used for irrigation. The major crops are corn grain, alfalfa, edible dry beans, corn silage, and sugar beets. Farmers almost exclusively use surface technologies for distributing water, including open ditches with siphons, and gated and flexible pipes with and without surge. They typically apply several irrigations per crop and season, each with a more or less fixed amount of water.

With a lack of on-farm data on yield responses to different water supplies for the study area, water-crop production functions were computed using a transient-state crop simulation model. The model was applied to the five main crops grown in the service area of NCLPIC assuming an average-weather year. The main features and results of the crop simulation model are summarized in the appendix. A detailed description including its input parameters is given by Scheierling, Cardon, and Young (1997).

While crop simulation models employed by economists typically treat the water input as a single value of water applied during the season, our model was adapted to capture the effects of irrigation timing as discrete-input events. The model outputs are water-crop production functions that show the impact of alternative irrigation schedules on consumptive use and yield. Appendix figure A1 presents estimates for alfalfa. Each point represents a relationship between yield (and, implicitly, consumptive use) and the number and timing of irrigation water applications. Using such production functions as an input in the economic model has two advantages. First, it allows us to incorporate irrigation scheduling as a decision variable of farmers faced with increasing water prices; and second, in addition to the conventional relationship between water application and yield, it provides estimates for the policy-relevant variable under consideration—i.e., the consumptive use associated with a given number and timing of irrigations.

A deterministic single-period linear programming model was developed to incorporate the physical relationships between water application and yield/consumptive use derived with the crop simulation model. Formulated for the long run, the economic model computes the net return-maximizing water applications in the study area in response to hypothesized alternative levels of water price, together with a derived demand for consumptive use. Changes in the output supply from the study area were not expected to be large enough to significantly affect regional product prices. An important assumption is that farmers are well informed not only about prices of inputs and outputs, but also about optimally timed irrigation schedules so that they apply limited irrigation water only in these combinations which result in the highest crop yields. Each crop can be irrigated with any of the five irrigation technologies. As in Caswell and Zilberman (1985), possible yield differences between technologies were not considered. These assumptions generated 245 activities.

Unit net returns were calculated for each activity based on the residual imputation approach (Young, 1996). These net returns are calculated as total revenue per acre (derived by multiplying the yield estimate from the simulation model by the crop price) minus variable costs (labor, materials, fuels, but exclusive of irrigation water costs) and annual overhead (including management) and annualized capital costs (inclusive of a land charge estimated at the value of the land in its next-best use, which is assumed to be the production of nonirrigated winter wheat). The resulting residual was imputed to the water resource and used as a value for net income in the objective function. Volatility and inflation were removed from crop prices by taking a five-year average of prices for the period 1989–1993 deflated with the GNP Implicit Price Deflator (Colorado Agricultural Statistics Service). Variable costs were taken from crop budgets for the Nebraska Panhandle (Selley, 1994) and adjusted to Weld County conditions based on the advice of Colorado State University extension agents. Alfalfa establishment costs were amortized over the average stand life in northeastern Colorado.

Constraints in the model were defined for land (the service area of NCLPIC, amounting to about 40,000 acres) and water deliveries. The latter include surface water (estimated based on average annual withdrawals from river flow and reservoir rights) and groundwater (estimated based on annual well allotments), and amount up to 120,324 acre-feet available in a typical year. An accounting constraint was formulated to measure consumptive use for each production activity. Other constraints were formulated to reflect the cropping pattern in the study area. Dry beans were limited to 17% of the total irrigated area, considering farmers' risk aversion as a result of highly variable bean prices. Sugar beets were allowed on no more than 7% of the area due to the contractual quotas imposed by the processor. Corn silage may be grown on up to 12% of the area, and alfalfa on up to 27% taking into account the magnitude of demand for fodder from nearby feedlots.

## Empirical Results

Computations from the economic model focus on the impact of hypothesized price increases on irrigation water deliveries and consumptive use for the study area. Three scenarios with varying on-farm adjustment possibilities to changes in water price were analyzed. Scenario 1 limits adjustments to changes in irrigated acreage and crop mix. It further assumes that the irrigation technology for the whole service area is open ditch with siphons, and the number of irrigations applied to each crop cannot be changed from the one which is optimal at the maximum water availability of 120,324 acre-feet. Growing crops with no irrigation is possible. Scenario 2 is similar to scenario 1, except the number of irrigations can be varied and decreased down to zero. Scenario 3 allows for the widest range of adjustments including changes in irrigated acreage, the crop mix, the number of irrigations, and irrigation technologies.

Results from parametric programming are reported in figures 1–4 and tables 1 and 2. Delivery demand functions for the three scenarios are shown in figure 1. As water price starts to rise from zero, the model indicates that deliveries are most quickly reduced in scenario 3, which allows for the most adjustment possibilities. Farmers in scenarios 1 and 2 with fewer adjustment options are initially much slower in reducing deliveries. As water prices reach very high levels, farmers in scenario 1 are predicted to be the first to stop irrigating, whereas farmers in scenario 3 continue to demand some irrigation water up to a water price of $292.

Figure 2 plots the results for consumptive use as a function of deliveries. In scenario 1, where adjustment possibilities are limited to changing irrigated acreage and cropping mix and switching to no irrigation, the model implies consumptive use would decline almost proportionally with deliveries. But consumptive use values decrease only very gradually in scenario 3 because farmers can switch to irrigation technologies with higher application efficiencies without much effect on consumptive use (and yields). At least initially, they can also reduce the number of irrigations without much impact on consumptive use. As shown by appendix figure A1, the number of irrigations for alfalfa, for example, can be reduced to five, or even four, before consumptive use values and yields change significantly. For scenario 3, this stage is predicted to set in when deliveries fall below about 52,000 acre-feet. When prices are so high that deliveries cease, farmers in all scenarios are likely to continue to grow on part of the land crops such as alfalfa which have positive net returns for zero irrigations, and thus consumptive use does not drop to zero.

Derived demand functions for consumptive use are shown in figure 3. With an almost linear relationship between deliveries and consumptive use, scenario 1 exhibits a consumptive use demand which, over a wide price range, is similar in shape to the corresponding delivery demand. In contrast, consumptive use demands under scenarios 2 and 3 are predicted to diverge substantially from their respective delivery demands. Specifically, although farmers with more adjustment options respond to rising water prices by decreasing deliveries, their consumptive use values decrease at a much slower rate. At very high prices in all scenarios, consumptive use coming from rainfall and drawdown of soil moisture is estimated to remain at about 20,000 acre-feet.

Figure 4 exhibits estimated net income of the irrigators in the service area of NCLPIC as a function of water deliveries. As water prices start to rise, net incomes in scenarios 1 and 2 fall relatively rapidly, while in scenario 3 changes in net income are initially

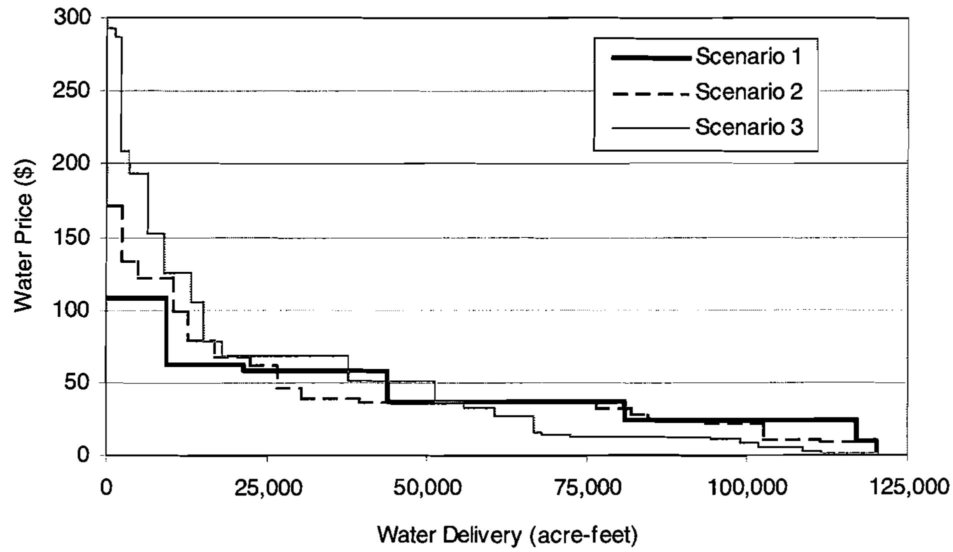


**Figure 1. Demand functions for water deliveries**

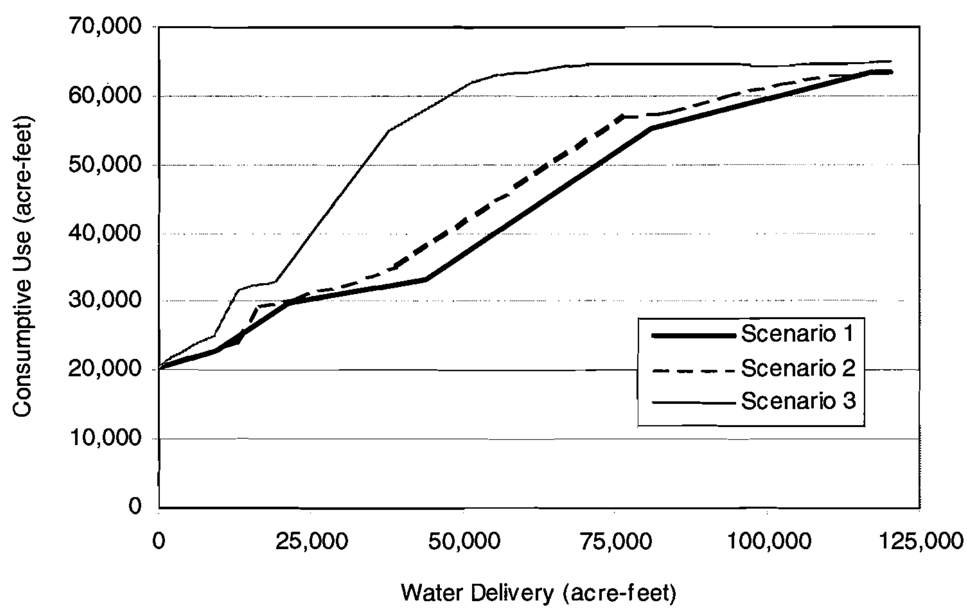


**Figure 2. Consumptive use as a function of water deliveries**

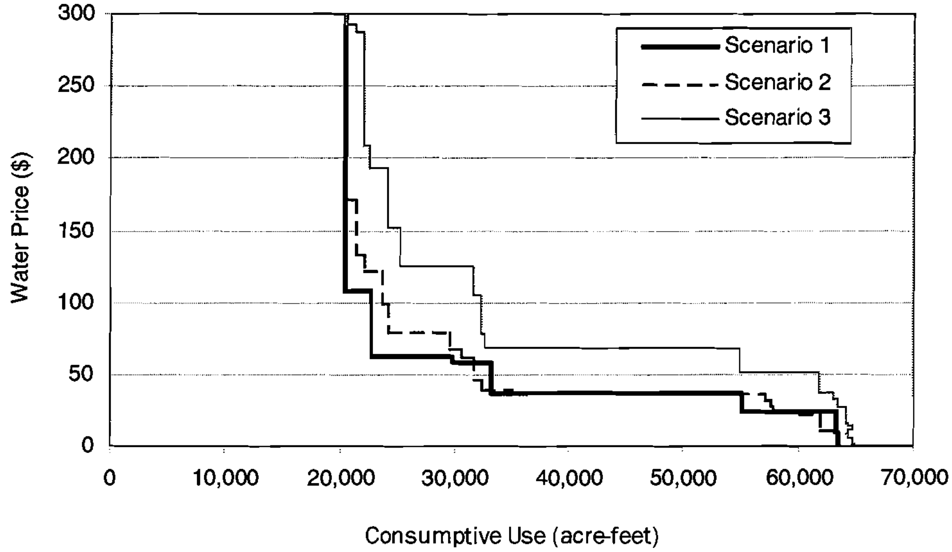


**Figure 3. Derived demand functions for consumptive use**

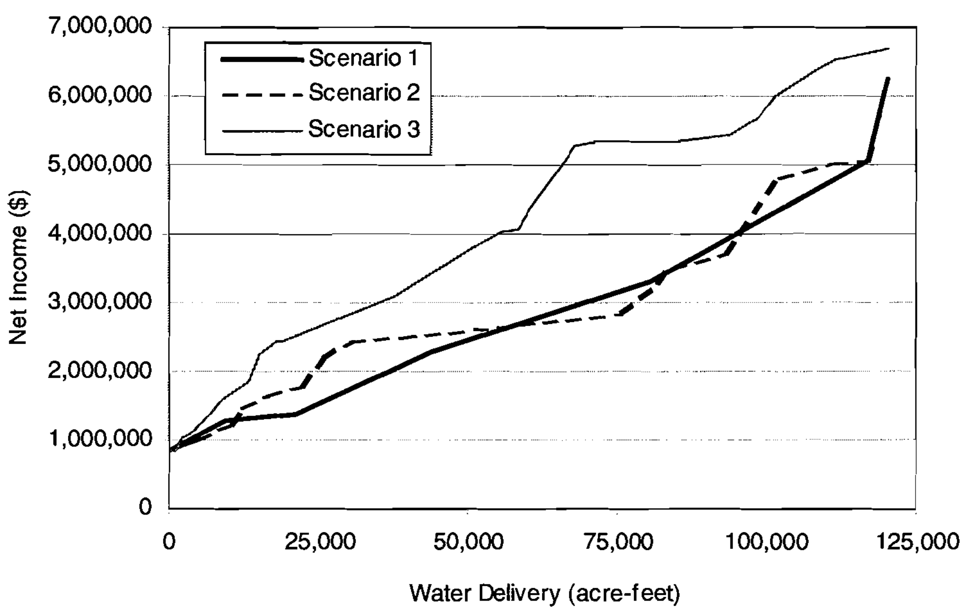


**Figure 4. Net income as a function of water deliveries**

much less dramatic. As water prices reach very high levels, farmers in all scenarios continue to earn a positive net income since they still have some crop production (and some consumptive use).

Under existing conditions in the lower South Platte Basin where irrigation water costs are quite low, water price increases in the lower ranges were considered to be the ones most relevant for examining the impact on deliveries and consumptive use implied by our analysis. The price changes included in table 1 comprise an increase from zero to $30, and from $30 to $60 per acre-foot of water. Changes in deliveries and consumptive use, as well as in net income, were examined in both absolute and percentage terms. For a price increase to $30 per acre-foot, scenarios 1 and 2 show decreases in deliveries of slightly less than a third, while the more realistic scenario 3 exhibits a relatively large reduction of nearly 50%. However, for a price increase to $60, deliveries in scenarios 1 and 2 with less adjustment options are much more reduced (by 82% and 78%, respectively) than in scenario 3 where the reduction amounts to 69%.

The predicted changes in consumptive use resulting from the two price increases tend to differ from the changes in deliveries depending on the adjustment options of the particular model formulation (table 1). That is, the more adjustment options a scenario allows, the larger the difference between changes in deliveries and consumptive use tends to be. The predicted difference is especially pronounced at a water price increase from $30 to $60 per acre-foot. Under scenario 1, for example, deliveries would be reduced by 82%, while consumptive use would decline by 53%. Under scenario 3, which allows for investments in improved water use efficiency, the reduction in consumptive use would be overwhelmingly smaller than the reduction for deliveries (15% as compared to 69%).

Reductions in net income associated with increased price are estimated to be highest in scenario 1 (table 1). At $30 per acre-foot, even though deliveries are only reduced by a third, net income decreases by more than half as a result of the pricing policy. Irrigators in scenario 3 still would receive 63% of their initial net income even though deliveries are reduced by half. At $60 per acre-foot, farmers in scenarios 1 and 2 are faced with a net income decrease of 79% and 70%, respectively, while farmers in scenario 3 still make 41% of their initial net income. This is because the potential to substitute capital for expensive water allows profitable production to persist in scenario 3 in contrast to the scenarios with more limited adjustment options.

To further illustrate the different effects of water price increases on deliveries and consumptive use, arc elasticities were calculated for delivery and consumptive use demands. The arc formula computes an elasticity at an average between two points, and allows for easy comparison between different scenarios (Tomek and Robinson, 1990). Table 2 reports implied elasticities for various price ranges. In the lowest price range (up to $30 per acre-foot), the demand for deliveries is more inelastic for scenarios 1 and 2 than for scenario 3 with more adjustment options, because initially these scenarios require relatively higher price increases for an adjustment, and thus a change in demand for deliveries, to take place. In the price range between $30 and $60 per acre-foot, the delivery demands for scenarios 1 and 2 become elastic, while the delivery demand for scenario 3 remains inelastic. As prices rise to higher levels, the model suggests that the delivery demands for all scenarios become elastic at some point. But especially for scenario 1, delivery demand tends to become more elastic faster because, as irrigation is ceased on more and more crops and irrigated acreage is given up,

**Table 1. Impact of Water Price Increases on Deliveries (af), Consumptive Use (af), and Net Income ($)**

| Description | at $0/acre-foot | at $30/acre-foot[a] | at $60/acre-foot[a] |
|---|---|---|---|
| | | **Deliveries** | |
| Scenario 1 | 120,324 | 80,968<br>(-32.7%) | 21,324<br>(-82.3%) |
| Scenario 2 | 120,324 | 81,964<br>(-31.9%) | 26,372<br>(-78.1%) |
| Scenario 3 | 120,324 | 60,584<br>(-49.6%) | 37,676<br>(-68.7%) |
| | | **Consumptive Use** | |
| Scenario 1 | 63,482 | 55,126<br>(-13.2%) | 29,915<br>(-52.8%) |
| Scenario 2 | 63,482 | 57,479<br>(-9.5%) | 31,596<br>(-50.2%) |
| Scenario 3 | 63,232 | 63,515<br>(-1.1%) | 54,928<br>(-14.5%) |
| | | **Net Income** | |
| Scenario 1 | 6,247,634 | 2,893,668<br>(-53.7%) | 1,327,760<br>(-78.8%) |
| Scenario 2 | 6,247,634 | 3,095,952<br>(-50.4%) | 1,852,804<br>(-70.3%) |
| Scenario 3 | 6,679,034 | 4,202,588<br>(-37.1%) | 2,748,836<br>(-58.8%) |

[a] Values in parentheses are percentage changes from the respective value at $0 per acre-foot of water delivery.

deliveries decrease more rapidly toward zero. (Switches to inelastic or perfectly inelastic estimates at some of the higher price ranges are caused by high "steps" in the demand curves, where deliveries are estimated to remain unchanged even though prices continue to rise.)

Consumptive use demand also tends to become less inelastic as water prices start to rise (table 2). But again, the predicted effects of increasing water prices are seen to depend on the scenario. The consumptive use demands for scenarios 2 and 3—which allow for more substitution possibilities as water cost increases—tend to be more inelastic than those of scenario 1. Further, consumptive use demands in all scenarios are more inelastic than their respective delivery demands over all price ranges. Thus the findings confirm that the price elasticity of consumptive use demand generally cannot be assumed to equal the price elasticity of delivery demand and, in particular, that the demand for consumptive use is likely to be much less price-responsive than the demand for deliveries.

The results reported in table 2 provide evidence that elasticity estimates for both delivery demand and consumptive use demand are very dependent on the model framework within which they are derived. In the model formulations where farmers' adjustment options are relatively limited, there is a strong correlation between deliveries and consumptive use. Yet for the more realistically formulated scenarios, the correlation between deliveries and consumptive use is likely to be much weaker. This is because

**Table 2. Price Elasticities of Delivery and Consumptive Use Demands**

| | Range of Water Price ($/acre-foot) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Description | 0–30 | 30–60 | 60–90 | 90–120 | 120–150 | 150–180 | 180–210 | 210–240 | 240–270 | 270–300 |
| **Delivery Demand:** | | | | | | | | | | |
| Scenario 1 | -0.20 | -1.75 | -1.96 | -10.86 | — | — | — | — | — | — |
| Scenario 2 | -0.19 | -1.54 | -1.76 | -0.71 | -5.67 | -14.43 | — | — | — | — |
| Scenario 3 | -0.33 | -0.70 | -2.13 | -0.50 | -1.61 | -1.98 | -6.04 | 0.00 | 0.00 | -25.00 |
| **Consumptive Use Demand:** | | | | | | | | | | |
| Scenario 1 | -0.07 | -0.89 | -0.68 | -0.61 | — | — | — | — | — | — |
| Scenario 2 | -0.05 | -0.87 | -0.66 | -0.08 | -0.47 | -0.31 | — | — | — | — |
| Scenario 3 | -0.01 | -0.22 | -1.30 | -0.08 | -1.01 | -0.23 | -0.61 | 0.00 | 0.00 | -0.97 |

Notes: Deliveries are estimated to become zero as water price reaches $108 per acre-foot in scenario 1, $172 per acre-foot in scenario 2, and $292 per acre-foot in scenario 3. Consumptive use in the respective scenarios is predicted to not change any further beyond these water prices.

delivery is an input factor which, at least to some extent, can be substituted with other input factors such as management (adaptation in the number of irrigations) and/or capital (change to irrigation technologies with higher application efficiencies). Model formulations incorporating these substitutions indicate that they enable farmers to significantly reduce deliveries in response to price increases; at the same time, they can prevent large reductions in consumptive use, and agricultural production, over a relatively wide price range.

The elasticity estimates are also influenced by the method used to calculate them. In our case, most elasticity values would be different if the endpoints between which the arc elasticities are calculated were changed. Therefore, the emphasis here is not on the particular magnitudes of the elasticity estimates, but on the direction of their change depending on the model formulation, the price range considered, and the focus on either delivery or consumptive use demand.

Our findings on the price elasticities of delivery demand are in line with previous results of linear programming models which indicated an inelastic demand for lower prices and a less inelastic demand for higher prices. However, they do not support the common presumption that in the case of an inelastic delivery demand, the use of pricing policy would not be very effective in bringing about reductions in deliveries—because, as the argument goes, even for relatively small reductions, large price increases would be required which in turn would cause large negative effects on income and wealth. Instead, this research suggests, especially for the more realistic scenarios with a range of adjustment options, an inelastic delivery demand does not necessarily imply that deliveries cannot be substantially reduced as the price rises. As tables 1 and 2 show, if in scenario 3 the price increases to $30 per acre-foot, the estimate of the delivery demand elasticity is -0.33 but deliveries would be reduced from 120,324 to 60,584 acre-feet.

The modeling approach presented focuses on farmers' responses to hypothesized increases in irrigation water prices. To empirically examine basin-wide hydrologic and ecological effects of rising irrigation water prices and reduced agricultural deliveries (and withdrawals), a river basin optimization model would have to be used such as, for example, Booker and Young (1994). Basin-wide effects are likely to include increased instream flows that could help restore river ecosystems. They could also involve improved water quality by leaving more native water in-stream for pollution dilution, and by reducing irrigation return flows with polluting salt, nutrient and pesticide loading.

## Policy Considerations

Our empirical results have important implications for irrigation water pricing policies in river basins where water is withdrawn from surface diversions and/or shallow alluvial aquifers, and where return flows constitute a significant part of the downstream water supplies. This would be the case in Colorado's South Platte Basin where annual surface withdrawals are estimated to amount to about 2.5 times the annual native surface water flows (South Platte Research Team, 1987), implying return flows are significant sources of downstream water supplies.

Based on results from the more realistic scenarios, even if delivery demands are price-inelastic, volumetric water charges could bring about large reductions in deliveries while not being very effective in reducing water consumption. They would also have the potential of altering basin hydrology, by reducing the magnitude and changing the timing of return flows. In the South Platte Basin, discharges from the alluvial aquifer (largely fed by irrigation return flows) increase late summer streamflows, which can help meet downstream irrigation demands for extended periods after peak runoff from snowmelt. The aquifer functions in the same manner as a reservoir, with irrigation withdrawals in excess of consumptive use contributing to storage and return flows representing releases (Smith et al., 1996). A water pricing policy that would significantly decrease deliveries, and return flows, could negatively impact water users who depend on these return flows downstream. Changes in the return flow regime could also impact groundwater levels and pumping costs. (Reduced return flows would not be a concern in the lower reaches of watersheds where there is no downstream dependence on return flows.)

If the goal is to make additional water available for alternative uses, in many river basins pricing of irrigation water deliveries would be a relatively ineffective policy instrument because, under realistic assumptions regarding potential farmer adjustments, net downstream river flows would not change much over a wide price range. In such hydrologic settings, the focus needs to be on measures that actually reduce consumptive use. Structural measures, such as land leveling or replacing open ditches with underground pipes, which mainly decrease transpiration from soil surfaces, would be one such approach. However, the amount of water involved is likely to be relatively small so that, without subsidies, the economic incentive for any single farmer to invest in such measures is minimal.

Larger quantities of water can be made available by changes in the crop mix, including switching to crops with lower seasonal consumptive use, or reducing irrigated acreage and switching to dryland crops. In the lower South Platte Basin, for example, farmers could switch from feed crops (alfalfa and corn) to vegetables such as carrots, which have a much lower water consumption and potentially generate much higher net income. However, these changes would involve making wholesale modifications in farm operations and entering a more dynamic marketing environment. Thus, they are not likely to occur on a widespread basis (Smith et al., 1996). To encourage such crop switches as well as potential transitions to rainfed agriculture or rangeland—which otherwise would only occur at very high water prices—subsidies or outright purchases of water rights would be necessary. Also, current federal subsidies for crops with high water consumption (such as sugar beets) might be reoriented to low-consumption/dryland crops in order to support increased water use in nonagricultural sectors.

If volumetric charges were imposed on consumptive use rather than on delivery amounts, irrigation water pricing could theoretically be an effective policy instrument for reducing the amount of water consumed. Similarly, the problems surrounding irrigation return flows could be avoided if the surface and ground water rights under the prior appropriation doctrine were converted from withdrawal or delivery to consumptive use amounts. But measuring and monitoring actual consumptive use would still be difficult and costly. Short of these changes, policies regarding water transfers need to emphasize the importance of consumptive use rather than withdrawals and deliveries.

## Conclusions

As water scarcity increases in the semi-arid West, it is often suggested that an appropriate pricing policy for irrigation water could reduce agricultural water use by providing stimuli for farmers to use water more efficiently, and make water available for higher valued nonagricultural uses. A number of earlier studies have noted that basin-wide water conservation depends less on changes in agricultural withdrawals and deliveries than on reductions in consumptive use. Our analysis extends this research by modeling both the demand for deliveries and the derived demand for consumptive use for a full range of hypothetical price changes.

Data from an irrigation company in Colorado's South Platte River basin were used as the basis for a water-crop simulation/linear programming approach designed to predict farmers' crop and water management responses to increasing water prices. In the context of the irrigation company, assuming an average-weather year, optimally timed irrigations, and a range of adjustment options, a hypothetical price increase from zero to $30 per acre-foot is estimated to reduce deliveries by half but consumptive use only by about 1%. This finding implies that a water pricing policy, or other methods of encouraging reduced deliveries, while maintaining the agriculture base, are not likely to make nearly as much additional water available for alternative urban or environmental uses as might be expected from a less realistic view of the hydrologic-economic interrelationships in irrigated agriculture. Moreover, a pricing policy would have a relatively large negative effect on agricultural net income and, correspondingly, on capitalized net income in farm land values.

Another finding of the analysis is that the estimated impact of the pricing policy depends on the particular model formulation. If adjustment options are relatively limited, the price-responsiveness of delivery demand and consumptive use demand differ little. But in a more realistic model formulation which also allows for adapting in the long run the number of irrigations and switching to more capital-intensive technologies with higher application efficiencies, the predicted consumptive use demand is significantly less responsive to increasing water prices than the delivery demand.

These results have important implications for potential water pricing policies in river basins where return flows constitute a significant part of the downstream water supplies. Our study finds that in such contexts, attempts to make additional water available for nonagricultural uses by raising irrigation water prices would be relatively ineffective in the long run because it would leave net downstream river flows and/or aquifer storage virtually unchanged. Making significant amounts of additional water available must rest on measures which actually reduce consumptive use. This will be most effectively accomplished by changes to low-consumptive use crops or to nonirrigated agriculture.

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## Appendix: Description of the Crop Simulation Model and Its Estimates Used in the Analysis

As noted in the text, water-crop production functions for the five main crops in the study area were estimated with a transient-state crop simulation model originally formulated by Cardon (1990). Its main features comprise the modeling of water and solute movement through the soil and the modeling of simultaneous water uptake by plants. With the model not formulated to calculate crop yield directly, values of water uptake were summed for the season and converted to yield following Doorenbos and Kassam (1979) who suggest a linear relationship between relative yield decreases and the deficit of relative evapotranspiration (consumptive use).

For predicting the effect of the potential range of numbers of irrigations, the model is formulated to allow up to nine irrigations on specified dates during the season. These values for the number of possible irrigations, though they represent the upper limit of the range of grower practice, are not uncommon. Thus alfalfa, corn grain, corn silage, and sugar beets may be irrigated from zero to nine times, while dry beans due to their shorter growing period are irrigated as many as eight times. On each of the nine specified irrigation dates, an irrigation event may or may not occur. This results in $2^8 = 245$ alternative irrigation schedules for dry beans, and $2^9 = 512$ alternative irrigation schedules for each of the other crops. Each irrigation event was assumed to consist of the same amount of net water infiltration into the soil, becoming available for plant water uptake or deep percolation. Typical net infiltration in Weld County, Colorado, is about three inches per irrigation. The amount of water which actually needs to be applied to achieve this net infiltration is higher depending on the irrigation technology used. In the

**Table A1. Comparison Between Measured and Computed Yields**

| Variable | Description | Measured Yield | Computed Yield |
|---|---|---|---|
| Alfalfa (tons/acre) | No irrigation | 2.0 | 2.7 |
| | Full irrigation | 5.1 | 4.9 |
| Corn Grain (bushels/acre) | No irrigation | 54.8 | 58.2 |
| | Full irrigation | 153.0 | 150.8 |
| Corn Silage (tons/acre) | No irrigation | N/A | 9.6 |
| | Full irrigation | 24.5 | 24.8 |
| Beans (cwt/acre) | No irrigation | 9.0 | 10.9 |
| | Full irrigation | 22.1 | 22.3 |
| Sugar Beets (tons/acre) | No irrigation | N/A | 12.8 |
| | Full irrigation | 24.0 | 24.3 |

Notes: Measured yield data are mean values for 1989–1992 from *Colorado Agricultural Statistics* (Colorado Agricultural Statistics Service, 1989–1993). Means for full irrigation are based on data for Weld County, Colorado. Means for no irrigation are based on data for northeastern Colorado. For corn silage and sugar beets, no data on dryland yields are available.

study area, the average application efficiency of open ditch with siphons is 30%, of gated and flexible pipe 40%, and of gated pipe with surge and flexible pipe with surge 60%. The other inputs to the crop production process besides water were assumed to be managed at a level so that water is the only limiting factor.

Yields estimated with the crop simulation model were compared to yields reported for the study area. Table A1 presents estimated yields for the "extreme" cases with no irrigation and full irrigation (i.e., eight irrigations for dry beans and nine irrigations for the other crops) and measured yields for non-irrigated (dryland) and irrigated crops. A comparison between computed and measured yields shows that the model predicts actual crop yields for the extreme cases reasonably well. Based on this result, the model estimates for the other cases are also believed to adequately represent actual conditions.

Figure A1 displays estimates for alfalfa yield resulting from the possible 512 combinations of irrigation events in the simulation model. Each point represents a relationship between yield (and, implicitly, consumptive use) and the number and timing of irrigations. Yield and consumptive use estimates as a function of irrigation events have similar shapes for the other crops, and are discussed in Scheierling (1995). The results of the simulation model provide a number of useful insights. First, depending on the timing of irrigation, the effect of a given number of irrigations on yield varies widely, particularly in the range between two and five irrigations. Second, when examining the optimally timed irrigation schedules (those which achieve the highest yield for a given number of irrigations), it becomes obvious that the increments in yield/consumptive use from additional irrigation events diminish as the number of irrigations increases. Third, there is only a weak correlation between the number of irrigations (the amount of irrigation water infiltrated) on the one hand and yield/consumptive use on the other. For example, when farmers have the option to optimally time irrigation events, an increase from seven to eight irrigations requires three inches of net water infiltration but contributes negligibly to an increase in yield/consumptive use; instead, it results in increases in soil moisture and deep percolation. When considering the amount of irrigation water which—depending on the application efficiency of the irrigation technology used—actually needs to be applied to achieve a net infiltration of three inches, the correlation is even less strong. This result implies farmers can to some extent substitute for additional irrigation water by reducing optimally timed irrigation events and by switching to irrigation technologies with higher application efficiencies without significantly impacting consumptive use and yield.

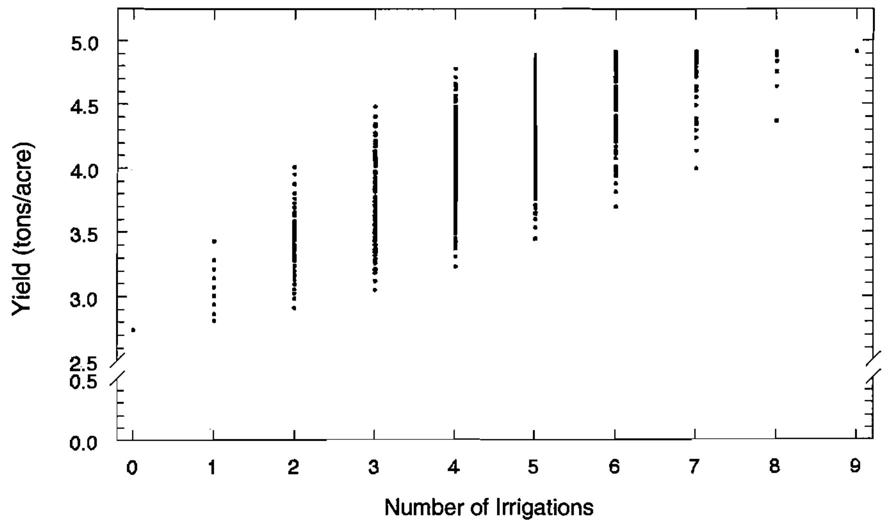


**Figure A1. Computed yield of alfalfa as a function of the number and timing of irrigations**