Public subsidies for water-conserving irrigation investments: Hydrologic, agronomic, and economic assessment

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[1] Public subsidies for promoting the adoption of water-conserving on-farm irrigation technologies are frequently cited as means for making additional water available for higher-valued uses in the water-scarce western United States. On the basis of an agroeconomic model reflecting conditions in northeastern Colorado, hypothetical conservation subsidy policies are analyzed with regard to their effects on hydrologic and agronomic factors such as irrigation water delivery, consumptive use, and return flows, as well as on economic factors including crop mix, input use, irrigation technology choice, and agricultural net returns to water. The cost-effectiveness of different subsidy arrangements for generating delivery reductions is also assessed, and implications for their implementation are derived. In contrast to assumptions underlying federal policies, the results confirm and extend earlier academic findings that subsidy policies are unlikely to provide real water conservation under many frequently encountered river basin conditions.

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1. Introduction

[2] In the western United States, growing urban water demands and a rise in the values placed on in-stream flows have intensified the competition for limited water supplies. With irrigated agriculture being by far the largest and often lowest-valued water use, efforts are increasingly undertaken to encourage agricultural water conservation with the aim of transferring some water to higher-valued uses and thus improving the economic efficiency of the allocation of scarce water resources. Since water losses are typically large in irrigated agriculture, adopting improved on-farm irrigation technologies is often cited as a promising approach for farmers to not only improve water use efficiency, but also conserve water for alternative uses while maintaining yield levels with little or no loss of income and avoiding adverse economic effects on the local community.

[3] To stimulate the transition to irrigation technologies with higher water-use efficiencies, interest is increasingly turning toward the provision of economic incentives, including instituting higher agricultural water prices or subsidizing investments in more water-efficient irrigation technologies [*Huffaker and Whittlesey*, 2003]. While water price reform may appear to be more appropriate and efficacious, in real-world applications, especially within the framework of the prior appropriation system of water law common in the western United States, this policy tool may conflict with state water law and would also have significant negative impacts on farm income and wealth [*Huffaker et al.*, 1998; *Michelsen et al.*, 1999; *Scheierling et al.*, 2004]. Attention is thus turning to the other approach, that of subsidizing water-conserving irrigation technologies.

[4] When assessing public subsidies for on-farm irrigation investments, it is useful to distinguish between water withdrawals, water deliveries, and consumptive use. Withdrawal measures the amount of water removed from the ground or surface water source. Delivery differs from withdrawal primarily by the amount of water lost in transit from the point of withdrawal to the point of delivery. Consumptive use is the amount of water that is evaporated, transpired, incorporated into plant products, or otherwise removed from the immediate water environment. Consumptive use differs from withdrawal by return flows, the amount returned to the water environment via surface runoff and/or deep percolation. Improved irrigation technologies can significantly increase on-farm irrigation efficiencies, i.e., the ratio of consumptive use to irrigation water delivered. They may also improve distribution uniformity. The resulting decrease in return flows may contribute to reducing the leaching of fertilizer and pesticides and to controlling soil erosion. These improvements, though, involve higher capital costs, which tend to be larger than the savings in input costs resulting from the decreases in irrigation water delivery at the farm level.

[5] A number of cost-sharing arrangements to promote irrigation investments have been developed by federal agencies involved in water resources management. For example, the U.S. Department of Agriculture has long provided assistance for upgrading irrigation systems. One of the priorities of the Environmental Quality Incentives Program initiated in 1997 is the conservation of ground and surface water resources. Cost-sharing may pay up to 75% of the costs of eligible conservation practices, which include the installation of more water-efficient on-farm irrigation technologies [*Natural Resources Conservation Service*

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(*NRCS*), 2004]. The U.S. Department of the Interior under the Yakima River Basin Water Enhancement Project Act is also authorized to provide public financing for improvements in on-farm irrigation efficiency and to earmark the reduction in withdrawals to increase the reliability of the water supply for both in-stream flows and irrigation [*Huffaker and Whittlesey*, 2000]. Under the Water 2025 initiative launched by the U.S. Department of the Interior in 2003, the Bureau of Reclamation, with the aim of conserving water and making it available for other needs, helps to modernize water storage and delivery systems, and works with state and local partners to improve water management with new technologies. Irrigation and water districts can apply for grants for investments to make more efficient use of existing water supplies [*U.S. Department of the Interior* (*USDI*), 2004]. In addition to these federal programs, expanding cities are increasingly called upon to help finance irrigation technology adoption in return for ‘‘saved’’ irrigation water, providing a supposed ‘‘win-win’’ solution for a knotty problem. Such proposals are currently being discussed to help solve the water needs of the fast growing urban areas in the Front Range region of northeastern Colorado.

[6] The common presumption that increasing agricultural water-use efficiency would provide a ‘‘new supply’’ of water for alternative uses has not gone unquestioned. Some early water resource economists such as *Hartman and Seastone* [1965] pointed out that only part of the water diverted from a stream is used consumptively, whereas the nonconsumptively used part typically returns to the stream as runoff, or percolates into the underlying groundwater deposits and becomes available for pumping. Using a simplified river system as an example, they illustrate that any change in these return flows (in magnitude, timing, or quality) may affect downstream users. *Huffaker and Whittlesey* [1995] and *Whittlesey* [2003] use similar examples to show that improvements in on-farm irrigation efficiency reduce water withdrawals or deliveries, but that in the presence of significant usable return flows this effect only appears to produce additional water. If the ‘‘saved’’ water is used to increase irrigated acreage, consumptive use may even increase.

[7] The contemporary literature on investments in water-conserving irrigation technologies can be divided into three strands. The first focuses on the adoption and diffusion of irrigation technologies, and has identified a number of factors affecting farmers’ technology choice. Since the 1980s, both normative and positive models have been developed. The normative literature is usually based on an engineering approach [*Caswell and Zilberman*, 1986; *Carey and Zilberman*, 2002], while the positive models econometrically test hypotheses using actual data on adoption decisions [*Caswell and Zilberman*, 1985; *Dinar and Yaron*, 1990; *Green et al.*, 1996]. Another strand of the literature that evolved during the 1990s develops optimization models to assess the transition to improved irrigation technologies as a water quality protection policy [*Caswell et al.*, 1990; *Knapp et al.*, 1990; *Wu et al.*, 1994]. This research examines the effects of farmers’ crop choice and irrigation investment decisions under different environmental conditions on the resulting quantity and quality of drainage water. More recently, a third strand of research challenges the assumption that water-saving investments designed to reduce deliveries will necessarily reduce basin-wide consumptive use. This line of research uses optimization-based spatial water allocation models to investigate optimal basin-wide investments in improving irrigation efficiency [*Umetsu and Chakravorty*, 1998; *Huffaker and Whittlesey*, 2000; *Chakravorty and Umetsu*, 2003]. These studies find that when return flows do not have value for downstream users, such as when drainage waters are highly saline or when they go directly to saline sinks or the sea, the switch to improved irrigation technology promotes basin-wide efficiency. However, in the more common situation, where return flows find their way to an aquifer or stream where they are available for reuse by irrigators, investments in improved distribution canals and better on-farm irrigation technologies that bring about reductions in demands for water deliveries may not save water from a basin-wide perspective.

[8] Although policy discussions frequently recommend public subsidies to encourage on-farm water conservation strategies, previous work on the effect of subsidies for irrigation investments is limited. *Caswell et al.* [1990] and *Wu et al.* [1994] consider subsidies as a policy tool for controlling irrigation-induced water pollution, and find that they would be effective in reducing both water applications and drainage return flows. With a focus on water conservation, *Huffaker and Whittlesey* [2003] develop a conceptual model of a single-crop representative farm where irrigable land is unconstrained. They study the farm’s response to a decrease in its share of investment costs for improving on-farm irrigation efficiency, showing that the farm increases its demands for water-saving investments and irrigated acreage and concomitantly, consumptive use. These changes may decrease or increase the demand for applied water. No empirical results are given beyond desribing optimality conditions for a farm with a single crop and no irrigation scheduling options.

[9] Our study aims at extending the literature assessing public subsidies for improved irrigation technologies by providing a detailed empirical assessment of the impacts of hypothetical subsidies on the relevant hydrologic, agronomic, and economic variables. By explicitly incorporating the whole range of on-farm responses (including adopting specific improved irrigation technologies, altering the crop mix and irrigated acreage, and changing the number of irrigation events) to public subsidies (including alternative cost-sharing levels), our research shows that subsidy policies can decrease water deliveries. However, subsidies may actually increase consumptive use even without an expansion in irrigated acreage, if it is profitable for farmers to use ‘‘conserved’’ water to apply additional irrigations to a crop. In river basins where return flows are important to downstream water users, subsidy policies are therefore unlikely to provide real water conservation. The analysis is based on an agroeconomic model combining a crop simulation model, which estimates the effect of alternative irrigation water delivery scheduling options on consumptive use and crop yield, with a mathematical programming model designed to reflect farmers’ optimal land, water use, and irrigation technology decisions under alternative costs of water application to farmers. The agroeconomic model is similar to that developed by *Scheierling et al.* [2004] to examine the impact of a water pricing policy on the demands for irrigation deliveries and consumptive use. In this study the

model is adapted to provide detailed presentation of the effects of different cost-sharing arrangements on hydrologic and agronomic factors such as delivery, consumptive use, and return flows, as well as on economic factors including crop mix, input use, irrigation technology choice, and agricultural net returns to water. Furthermore, the model allows us to assess the cost-effectiveness of the subsidies for generating water delivery reductions and derive implications for their implementation. The model estimates are based on data from a representative irrigation organization in northeastern Colorado. Results indicate that the potential of a subsidy policy for real water conservation depends mainly on whether the unconsumed portion of the deliveries is irretrievably lost or forms an important part of the downstream water supply, but also on its design, and on the on-farm responses available to farmers.

2. Study Area

[10] The New Cache La Poudre Irrigation Company, one of about a dozen farmer-owned irrigation organizations along the South Platte River in Weld County, Colorado, was chosen as the study area. Dating back to the late nineteenth century, these cooperative irrigation organizations in the upper South Platte basin often own the most senior water right decrees for surface flows, which under Colorado's prior appropriation system guarantee highly secure and reliable water supplies. A water right is defined as the right to have delivered a certain amount of water at a specific location for beneficial use. The right can be transferred as long as other water rights holders are not injuriously affected [*Getches*, 1997]. The courts usually consider the historical use of the right and require that the water consumption of the new use is not greater than the historical consumptive use. This limitation is designed to protect other water rights holders dependent on the return flow regime, by aiming to ensure stream conditions present at the time of their respective appropriations.

[11] Return flows are very important in the South Platte basin. Deep percolation from ditches and irrigated land reaches the river's unconfined shallow alluvial aquifer, where it becomes available for pumping or to replenish surface flows downstream. On the basis of comparisons of basin inflows to total surface and groundwater withdrawals, the water in Colorado's portion of the South Platte basin is estimated to be used and reused by a factor of about 2.5 before it reaches Nebraska [*South Platte Research Team*, 1987]. More than 80% of the withdrawals in the South Platte basin continue to be used for irrigated agriculture, but there is increasing pressure to make some of that irrigation water available for growing urban and environmental demands. Policies encouraging a faster adoption of improved irrigation technologies are frequently suggested.

[12] Farmers in the upper South Platte basin rely mostly on surface irrigation, with open ditch with siphon tubes the traditional and still dominant technology [*Frasier et al.*, 1999]. They also use gated pipes made from PVC or flexible pipes made from plastic, sometimes with an automatic surge valve installed between two sets of pipes that allows the water to alternate between the left and right side of the valve to limit drainage losses. Sprinklers are increasingly found in the lower South Platte basin on lands with uneven slopes and toward the state border with Nebraska, where a higher percentage of the irrigation water is derived by pumping from the tributary aquifer.

[13] The literature on the adoption of irrigation technologies mentioned earlier has identified numerous variables affecting farmers' technology choice. The major economic factors are commodity prices, costs of inputs, and the costs of implementing the improved irrigation technology. The roles of accumulation and distribution of knowledge, uncertainty, and irreversibility in technology choice are also increasingly stressed. Significant environmental factors comprise climate, topography, and land quality. Among the institutional factors are water rights and land tenure arrangements. Although the results from different studies differ in the weight given to particular factors, it appears that improved irrigation technologies are more likely to be adopted on lower-quality land (because of improved uniformity benefits), when prices of crops, water, and labor inputs are high, and when the cost of switching technologies is low. Also, extreme events like droughts tend to increase adoption rates. On the basis of these findings, it is not surprising that in the case of the irrigation organizations in the upper South Platte basin, with the availability of secure and inexpensive water sources for agriculture, mostly high quality agricultural land, relatively inexpensive unskilled labor, and continued low real crop prices, the transition to improved irrigation technologies has been relatively slow.

3. Agroeconomic Model

[14] An agroeconomic model was developed to simulate crop production decisions and irrigation management and technology options available to farmers in the representative irrigation organization when a policy for subsidizing improved irrigation technologies is introduced. The agronomic part consists of a complex transient-state simulation model of the type originally formulated by *Cardon and Letey* [1992a, 1992b]. It was adapted to estimate water-crop production functions that can capture the effects of irrigation timing as discrete-input events as described by *Scheierling et al.* [1997].

[15] The main features of the simulation model include modeling of water and solute movement through the soil and modeling of simultaneous water uptake by plants. Values of water uptake are 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). To simulate the impact of scheduling options on consumptive use and yield, a number of irrigation events are modeled for each crop. Each irrigation is assumed to consist of the same amount of net water infiltration into the soil, becoming available for plant water uptake or deep percolation. The amount of water which actually must be applied to achieve this net infiltration depends on the irrigation technology chosen. The other inputs to the crop production process besides water are assumed to be managed at a level so that water is the only limiting factor.

[16] The outputs of the crop simulation model are water-crop production functions that show the impact of alternative irrigation schedules on water deliveries, consumption, and crop yield. Used as inputs in the economic model, these production functions allow incorporation of irrigation

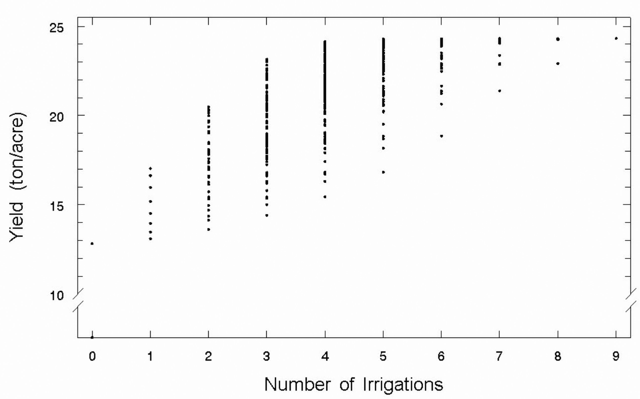

Figure 1. Estimated yield of sugar beets as a function of number and timing of irrigations.

scheduling as a decision variable of farmers, and provide estimates of consumptive use associated with a given number and timing of irrigation events.

[17] The economic model is a deterministic single-period linear program formulated for the long-run planning context. For any particular subsidy policy, it calculates the choice of crop mix, irrigated acreage, number of irrigations, and irrigation technologies that maximizes the net income in the irrigation district, as well as the implied water delivery and consumptive use amounts. Activities included in the model are the main crops of the study area, which can be irrigated with different irrigation technologies and treated with varying numbers and timing of irrigations. Farmers are assumed to be well informed about the water-crop production functions, including the optimally timed irrigation schedules, and to apply limited water only in these combinations which result in the highest crop yields for the available water.

[18] On the basis of the residual imputation approach [*Young*, 2005], unit net incomes per acre are calculated for each activity by subtracting from total revenue per acre the variable costs (including groundwater pumping, labor, materials and fuels but at this stage, exclusive of fixed irrigation water costs), the annual overhead (comprising management), and annualized capital costs (including a land charge estimated as the opportunity cost or the value of land in its next best use, which is the production of dryland winter wheat). The unit net incomes are used in the objective function. Constraints in the model are defined for land and typical annual water deliveries. An accounting constraint is included to measure consumptive use. Other constraints are formulated to reflect the cropping pattern in the study area. The net return to water for farmers in the irrigation organization is calculated as net income emerging from the objective function minus fixed irrigation cost. Changes in the output supply from the study area are not expected to be large enough to significantly affect regional product prices.

[19] By using an optimization model, the implicit assumption regarding farmers' adoption behavior is that they will upgrade to an improved irrigation technology when the expected net return under a subsidy approach is greater than the net return to be gained from continuing the former irrigation practice. The model thus predicts the long-run equilibrium for the choice of irrigation technologies and the related hydrologic, agronomic, and economic factors.

4. Data and Model Specification

[20] To assess the effects of different cost-sharing arrangements for irrigation investments, the framework of the agroeconomic model was applied to the area served by the New Cache La Poudre Irrigation Company. The irrigation organization enjoys an adequate water supply, including senior rights for river flow, and rights to water from local reservoirs that is mostly used in the late season. Some irrigators also own shares in the federal Colorado–Big Thompson transmountain water diversion project. In addition, irrigators have well permits for pumping groundwater. In a typical year, farmers use about 60,000 acre-feet (1 acre-foot = 1234 m^3) of surface water and pump approximately the same amount to irrigate an area of 44,000 acres (1 acre = 4047 m^2). Loam soil is the predominant type in the study area.

[21] Corn grain (maize) and alfalfa are the most important crops, while edible dry beans, corn silage, and sugar beets are also significant. Assuming long-term average weather patterns, water-crop production functions are estimated for these five main crops. Corn, alfalfa, and sugar beets are assumed to receive up to nine irrigations on specified dates during the season, and beans (with a shorter growing season) are assumed to receive up to eight irrigations. The typical net infiltration per irrigation event in the study area is about 3 inches (1 inch = 2.54 cm). The yields for the five crops estimated with these assumptions were compared with yields reported in the study region. In particular, a comparison between computed yields for the "extreme" cases with no irrigation and full irrigation and measured yields for nonirrigated (dryland) and irrigated crops showed that the model predicts reasonably well. In the case of sugar beets, for example, the computed yield for full irrigation was 24.3 t/acre compared with a mean value based on data for Weld County, Colorado, of 24.0 t/acre [*Scheierling et al.*, 1997].

[22] To illustrate the outputs of the crop simulation model, yield estimates for all possible combinations of discrete irrigation events for sugar beets are displayed in Figure 1. Yields vary widely as a function of the number and timing of irrigations. As expected, when farmers can choose the optimal timing of irrigations, i.e., those that achieve the highest yield for a given number of irrigations, the increments in yield from additional irrigation events diminish as the number of irrigations increases. Thus there is not a strong relation between the number of irrigations (the amount of irrigation water infiltrated) and yield (and consumptive use). When considering the amount of water that, depending on the irrigation technology used, actually needs to be delivered to achive a net infiltration of 3 inches, the relation is even weaker.

[23] Yield estimates from the crop simulation model were used to calculate total revenue per acre. Volatility and inflation were removed from crop prices by taking a 5-year average of prices for the period 1989–1993 deflated with the GNP implicit price deflator (see http://www.nass.usda.gov/Statistics_by_State/Colorado/index.asp). Variable costs were taken from crop budgets for the Nebraska Panhandle [*Selley*, 1994] and adjusted to Weld County conditions

Table 1. Assumed Characteristics of On-Farm Irrigation Technologies

Description	Open Ditch With Siphon Tubes	Gated Pipe	Gated Pipe With Surge	Flexible Pipe	Flexible Pipe With Surge
Application efficiency, %	35	55	65	50	60
Water application,[a] acre-foot/irrigation per acre	0.71	0.46	0.38	0.50	0.42
Labor requirement, hours/irrigation per acre	0.75	0.50	0.25	0.50	0.25
Average annualized capital cost,[b] $/acre	2.23	14.07	27.74	11.99	23.72

[a]Typical net infiltration in Weld County, Colorado, is about 3 inches per irrigation (or 0.25 acre-foot per irrigation per acre). The amount of water to be applied to achieve this net infiltration depends on the application efficiency of the respective irrigation technology.
[b]Operation and maintenance costs and thus total annual costs for each irrigation technology vary with the number of irrigations.

based on the advice of Colorado State University extension agents.

[24] Farmers in the irrigation organization use open ditch with siphon tubes to distribute water on more than half of the irrigated area. The remaining land is served mostly by gated and flexible pipes with and without surge. Sprinklers irrigate about 10% of the service area. In the modeling exercise the five surface irrigation systems are considered. The assumptions regarding these systems are in Table 1. Depending on the respective average application efficiency, the amount of water required to achieve the typical net infiltration per irrigation varies for each irrigation technology. Irrigation distribution is implicitly assumed uniform for these irrigation systems, with the net infiltration of 3 inches representing an average value on a given field. Possible yield differences between the surface irrigation systems are considered to be negligible. (Sprinklers, which tend to have irrigation events with smaller water applications and higher frequencies than surface irrigation systems, are not included in the modeling exercise. Because sprinklers' high flexibility of meeting irrigation requirements at critical growth stages, they typically result in higher yields and consumptive use. Their inclusion would have required the explicit consideration of distribution uniformity for determining their productivity. Methods are being considered to account for distribution uniformity in the crop simulation we have used, but it currently requires that the model be run over a range of water input values at multiple points to get a weighted-average productivity, an exercise not possible within the research resources available for this analysis.)

[25] To reflect the cropping pattern in the area served by the irrigation organization, sugar beets were limited to 6% and dry beans were limited to 15% of the total irrigated area. Corn silage may be grown on up to 11%, and alfalfa may be grown on up to 25% of the area. The area for corn grain was not constrained. Each crop can be irrigated with any of the five irrigation technologies and receive up to nine irrigations (beans up to eight). These assumptions generated 245 activities for which unit net incomes were calculated and included in the economic model.

5. Results: Predicted Effects of Irrigation Technology Subsidies

[26] Computations from the economic model focus on the impacts of hypothesized subsidy policies on hydrologic, agronomic, and economic variables. As a first step, the linear programming model was solved to establish the base case with zero subsidy. Under this scenario, farmers are predicted to irrigate all 44,000 acres of the service area and fully use the available surface and ground water of about 120,000 acre-feet. All five crops are grown (corn grain on 18,800 acres, alfalfa on 10,800 acres, dry beans on 6800 acres, corn silage on 4800 acres, and sugar beets on 2800 acres). The irrigation water costs (including fixed charges for the services of the irrigation organization and other fees, annualized capital cost, and operation and maintenance cost for the wells, as well as electricity charges for groundwater pumping) amount to $2.1 million, and the labor costs for operating and maintaining the irrigation technologies amount to $0.7 million. The agricultural net return to water is estimated to be $5.0 million.

[27] According to the optimal base case solution, open ditch with siphon tubes is used for 67% of the service area. This corresponds well with the actual situation in the irrigation organization. Flexible pipe is used on part of the corn silage area as well as on alfalfa and sugar beets. Alfalfa and sugar beets would be irrigated five times, while corn grain, corn silage, and dry beans would receive four irrigations. In the absence of other constraints, the model tends to choose numbers of irrigations in the range from four to six per season because independent of the irrigation technology used, these combinations are estimated to have the highest unit net incomes. Although yields and gross revenues would slightly increase with more irrigations, the operation and maintenance costs (including the cost of applying more water) tend to increase at a faster rate and thus depress unit net incomes.

[28] To examine the effects of different cost-sharing arrangements for irrigation investments, the proportion of the average annualized irrigation system improvement capital cost (shown in Table 1) paid by the farmer and the public agency providing the cost-sharing was varied. Specifically, the percentage of capital cost paid by the public agency was parametrically increased from zero to 100% in 20% increments. With this assumption, four scenarios with alternative policy formulations and on-farm responses were analyzed. Scenario 1 assumes the availability of a subsidy for the adoption of any irrigation technology improvement (e.g., for a switch from open ditch with siphon tubes to flexible pipe or from gated pipe to gated pipe with surge), and allows a wide range of possible on-farm responses, including an upgrading of irrigation technology, changes in crop mix, adjustments (but no expansion) in irrigated acreage, and changes (including an increase) in the number of irrigations. Scenarios 2 and 3 are formulated like scenario 1, except that scenario 2 excludes the option of increasing the number of irrigations from the base case while scenario 3 permits an expansion in the irrigated acreage (the land constraint is relaxed to 46,000 acres from 44,000 acres in

the base case). Scenario 4 incorporates the same on-farm responses as scenario 1 but limits the provision of a subsidy to the switch to the most water-efficient technology, in this case gated pipe with surge, which has the highest application efficiency (and capital cost requirement) of the five surface irrigation systems.

[29] Of the four scenarios, the most realistic in representing the situation in the study area would be scenario 1. Federal programs such as the Environmental Quality Incentives Program do not limit their cost-sharing incentives to any particular irrigation investment. Also, the assumptions with regard to farmers' responses are in line with Colorado's prior appropriation system and its rules regarding the use of water that is "saved" as a result of measures such as irrigation investments. The general rule is that this water may only be used by the owner as long as it is on the original land and for the original purpose of the water right [*Getches*, 1997]. Thus an expansion of irrigated area beyond the original land to which the water rights of the irrigation organization apply (i.e., 44,000 acres) would not be possible without court permission, with the court having to be convinced that the water consumption on the expanded area would not be greater than the historical consumptive use on the original area. However, the purpose of the water right is not considered to be changed if the "saved" water would be used in a new manner for the same general purpose (in this case, irrigated agriculture), such as by increasing the number of irrigations (even though downstream users may actually be harmed by the associated increase in consumptive use). While scenario 1 may be closest to the actual situation in the study area, scenario 2 reflects the common presumption that farmers as a result of a subsidy policy may switch to an improved irrigation technology but otherwise would not change their production activities. In contrast, the formulation in scenario 3 assumes that as long as it is profitable, farmers will try to adjust their production activities to make use of the water "saved" from the transition to a more water-efficient irrigation technology, including by increasing numbers of irrigations and irrigated acreage. Finally, scenario 4 reflects a situation where a public agency, possibly intent on increasing the effectiveness of a subsidy program, limits financial support to the adoption of only the most water efficient technology.

[30] Model results for the four scenarios are presented in Tables 2 and 3. In discussing results, it is first assumed that the unconsumed portion of irrigation water deliveries becomes fully available for downstream use. Predictions for the main annual hydrologic, agronomic, and economic effects of irrigation technology subsidies are in Table 2. Across all scenarios, results confirm that subsidies do encourage a shift to more water efficient technologies. By covering a share of the capital cost, they lower farmers' irrigation costs. Because of the reductions in deliveries, they also lead to savings in other variable costs such as water cost (groundwater pumping) and labor cost. As the level of subsidies paid by the public agency rises (and as long as they induce a technology transition), the model suggests continuing decreases in deliveries. At the same time, net return to water grows, partly as a result of the increasing subsidy amount and partly because of reductions in input use. Consumptive use in all scenarios is never predicted to fall below the level of the base-case solution. As a result, the ratio of consumptive use to irrigation water delivered rises as deliveries decrease. This ratio is one way to look at overall efficiency in the system, but it is not the same as the traditional measure of irrigation application efficiency which only compares irrigation applications to consumptive use for the period of the irrigation interval. Consumptive use reported in Table 2 includes use of stored soil moisture and in-season precipitation which are credited toward consumptive use when calculating an irrigation requirement. Nevertheless, the ratio of consumptive use to water delivered offers a relative value useful in comparing overall efficiencies of the different scenarios modeled. Independent of the particular scenario specification, all land in the service area would be irrigated, with the cropping pattern remaining the same as in the base case (which is due mainly to the model constraints reflecting the current cropping pattern), except in scenario 3, where the area grown with corn grain would increase by 2000 acres as the land constraint is relaxed by the same amount.

[31] There are also major predicted differences among the alternative scenarios. In scenario 1, when a subsidy amounting to 20% of the capital cost for any improved technology is introduced, the area irrigated with flexible pipe is predicted to increase from 33% in the base case to 100% (and the area irrigated with open ditch with siphon tubes to decrease from 67% to zero). The adoption of flexible pipe leads to a reduction in demanded water deliveries of about 21%. Water consumption, and the number of irrigations for each crop, are predicted to remain the same as in the base case up to a subsidy level of 60%. At the 80% level the optimal irrigation events for corn grain and corn silage increase from four to five, with a concomitant small increase in consumptive use of 323 acre-feet. About 85% of the area is switched to the more water efficient flexible pipe with surge. As the subsidy reaches 100%, the whole area would be under flexible pipe with surge. (Although gated pipe and gated pipe with surge have higher irrigation application efficiencies, using them would be less profitable.) The ratio of consumptive use to water delivered would rise to 80% from 59% in the base case, while return flows are reduced by almost 32,000 acre-feet or 64% over the base case. Overall, as subsidy levels increase, net return to water is predicted to grow.

[32] In scenario 2, the initial consumptive use amount would not change at any subsidy level. The impact of the subsidy policy would be the same as in scenario 1 up to the 60% subsidy level. Beyond that, net return to water is lower because the number of irrigations (and therefore yield) cannot increase as in scenario 1. At the 100% subsidy level the same irrigation technology as in scenario 1 (flexible pipe with surge) is used for the entire area. However, the reduction in deliveries (and correspondingly in return flows) is significantly higher and the most dramatic among all scenarios. The ratio of consumptive use to water delivered would reach 90%.

[33] Scenario 3 generates the same technology switches, number of irrigation events, and cropping patterns as scenario 1, except that the area grown with corn grain would be expanded from 18,800 to 20,800 acres. This results in higher increases in net return to water and consumptive use, and smaller reductions in water and labor

Table 2. Predicted Annual Hydrologic, Agronomic, and Economic Effects of Irrigation Technology Subsidies

Subsidy Level, %	Water Deliveries, acre-feet/yr	Water Cost, $/yr	Labor Cost, $/yr	Net Return to Water, $/yr	Consumptive Use, acre-feet/yr	Return Flows, acre-feet/yr
Base Case (No Subsidy)						
0	120,324	2,067,067	746,874	4,968,508	70,787	49,537
Scenario 1 (Subsidy for the Adoption of Any Irrigation Technology Improvement)						
20	94,850	2,013,826	568,800	5,055,630	70,787	24,063
40	94,850	2,013,826	568,800	5,161,230	70,787	24,063
60	94,850	2,013,826	568,800	5,266,390	70,787	24,063
80	90,976	2,005,730	360,600	5,406,946	71,110	19,866
100	88,732	2,001,040	319,800	5,612,920	71,110	17,622
Scenario 2 (Like Scenario 1 but Without a Potential Increase in the Number of Irrigations)						
20	94,850	2,013,826	568,800	5,055,630	70,787	24,063
40	94,850	2,013,826	568,800	5,161,230	70,787	24,063
60	94,850	2,013,826	568,800	5,266,390	70,787	24,063
80	89,088	2,001,784	466,800	5,391,380	70,787	18,301
100	79,056	1,980,817	284,400	5,588,379	70,787	8,269
Scenario 3 (Like Scenario 1 but With a Potential Expansion of the Irrigated Acreage)						
20	98,800	2,022,082	592,800	5,259,870	73,845	24,955
40	98,800	2,022,082	592,800	5,370,270	73,845	24,955
60	98,800	2,022,082	592,800	5,480,210	73,845	24,955
80	95,136	2,014,424	375,600	5,626,552	74,195	20,941
100	92,892	2,009,734	334,800	5,842,005	74,195	18,697
Scenario 4 (Like Scenario 1 but Subsidy Only for the Adoption of the Most Water Efficient Technology)						
20	120,324	2,067,067	746,874	4,968,508	70,787	49,537
40	120,324	2,067,067	746,874	4,968,508	70,787	49,537
60	120,324	2,067,067	746,874	4,968,508	70,787	49,537
80	90,872	2,005,512	401,400	5,010,913	71,110	19,762
100	81,896	1,986,753	319,800	5,251,839	71,110	10,786

Table 3. Predicted Cost-Effectiveness of Irrigation Technology Subsidies in Terms of Water Delivery Reduction

Subsidy Level, %	Water Delivery Reduction Over Base Case, acre-feet/yr	Total Subsidy Cost, $/yr	Unit Subsidy Cost, $/acre-foot/yr	Net Return Increase Over Base Case, $/yr	Unit Net Return Increase, $/acre-foot/yr
Scenario 1 (Subsidy for Adoption of Any Irrigation Technology Improvement)					
20	25,474	71,230	2.80	87,122	3.42
40	25,474	142,459	5.59	192,722	7.57
60	25,474	213,392	8.38	297,882	11.69
80	29,348	771,268	26.28	438,438	14.94
100	31,592	1,043,680	33.04	644,412	20.40
Scenario 2 (Like Scenario 1 but Without a Potential Increase in the Number of Irrigations)					
20	25,474	71,230	2.80	87,122	3.42
40	25,474	142,459	5.59	192,722	7.57
60	25,474	213,392	8.38	297,882	11.69
80	31,236	542,750	17.38	422,872	13.54
100	41,268	1,043,680	25.29	619,871	15.02
Scenario 3 (Like Scenario 1 but With a Potential Expansion of the Irrigated Acreage)					
20	21,524	76,030	3.53	291,362	13.54
40	21,524	152,059	7.06	401,762	18.67
60	21,524	227,772	10.58	511,702	23.77
80	25,188	809,228	32.13	658,044	26.13
100	27,432	1,091,120	39.78	873,497	31.84
Scenario 4 (Like Scenario 1 but Subsidy Only for the Adoption of the Most Water Efficient Technology)					
20	0	0	0.00	0	0.00
40	0	0	0.00	0	0.00
60	0	0	0.00	0	0.00
80	29,452	825,468	28.03	42,405	1.44
100	38,428	1,220,560	31.76	283,331	7.37

costs, than in scenario 1. At each level of subsidy, an additional amount of about 4000 acre-feet of water would be delivered that in scenario 1 was ‘‘saved’’ because irrigated acreage remained unchanged. If the land constraint were relaxed by more than 2000 acres, an even higher amount of the otherwise ‘‘saved’’ water deliveries would be spread on the additional land, leading to further growth in consumptive use (and net return).

[34] In scenario 4, no technology switches and thus no change from the base case would occur up to the 60% subsidy level. This is because the estimated unit net incomes for the crops irrigated with gated pipe with surge are lower than the unit net incomes achieved with other, less water efficient technologies. When the subsidy level reaches 80%, about 85% of the service area would be irrigated with gated pipe with surge. As in scenario 1, consumptive use would rise by 323 acre-feet above the base case because irrigation events for corn grain and corn silage increase from four to five. At the 100% subsidy level the entire area is predicted to be under gated pipe with surge, which causes water deliveries to be significantly lower than in scenario 1. Net return to water is lowest among the four scenarios.

[35] Overall, the results in Table 2 suggest that a subsidy policy is unlikely to diminish consumptive use under any of the scenarios. In fact, consumptive use (and yield) levels are likely to increase if the number of irrigation events is not constrained to be the same as in the no-subsidy situation. Further, if irrigated acreage is also allowed to increase, the potential rise in consumptive use is even higher. Therefore, in river basins where downstream users depend on the unconsumed portion of deliveries in the form of return flows, subsidies for technology investments would be unlikely to bring about a ‘‘new supply’’ of water but would likely lead to an actual increase in consumptive use.

[36] Moreover, if 100% of the unconsumed water deliveries become available as return flows, and consumptive use remains unchanged, the results show that a subsidy policy would simply redistribute basin water; it leaves more water in the stream or aquifer from where the deliveries originate and reduces return flows correspondingly. Both an increase in consumptive use and a redistribution of water between the aquifer and the stream may result in damages to downstream users, the extent of which would depend on when and on whom the losses of water would be registered.

[37] Situations exist where a subsidy policy may explicitly aim at creating savings in water deliveries and concomitantly, reductions in return flows. This could be appropriate in basins where runoff and seepage from irrigated lands are irretrievably lost (as to the sea), where the exclusive water source is deep groundwater and/or where drainage pollution and erosion problems are an overriding concern. Results in Table 2 indicate that overall, higher subsidy levels would encourage larger delivery reductions. Also, a policy requiring a switch to an irrigation technology with a higher water efficiency combined with a high subsidy level, and farmers unable to increase irrigated acreage and/or irrigation events, would lead to larger delivery savings.

[38] To assess the cost-effectiveness of the different subsidy arrangements for generating delivery reductions, total subsidy cost and subsidy cost per acre-foot delivery reduction are presented in Table 3. Some features are common across scenarios. Total subsidy cost rises with higher levels of subsidy, but surprisingly, its rise is almost exponential. In scenario 1, for example, changing the subsidy level from zero to 20% would cost the public agency only around $71,000, but from 80% to 100% almost 4 times that amount. The unit subsidy cost also rises with the subsidy level. In scenario 1 it would be less than $3.00 per acre-foot at the 20% subsidy level and over $33.00 at the 100% level.

[39] Scenario 2 seems to be the most cost-effective among the scenarios. Up to a subsidy level of 60%, unit subsidy costs would be the same as in scenario 1 but beyond that, significantly lower due to higher reductions in water deliveries. Scenario 3, with farmers able to increase irrigation events and irrigated acreage, would create the highest unit subsidy cost at each subsidy level. Somewhat counterintuitively, limiting subsidies to the most water efficient irrigation technology as in scenario 4 would not necessarily be cost-effective. Total subsidy cost at the 80% and 100% levels, when the policy at last begins to have an impact, are the highest of all scenarios.

[40] Overall, the results suggest that an agency trying to maximize water delivery reductions with a given amount of financial resources should provide a lower level of subsidy to a larger number of farmers (rather than a higher level of subsidy to fewer farmers), while ensuring that irrigation events and, in particular, irrigated acreage are not increased. At least in the case of surface irrigation systems, this is predicted to result in the lowest subsidy cost per acre-foot of delivery reduction.

[41] Table 3 also displays net return increases over the base case, and net return increases per acre-foot reduction in delivery. Across scenarios, net return increases tend to be larger the higher the subsidy level (as long as the level is set high enough to induce a technology transition). This is because farmers benefit from the cost-sharing arrangements and also from the savings in energy and labor costs. Yet in the scenarios which allow subsidies for any irrigation technology improvement, the magnitude of the increase seems to be inversely related to the delivery reduction, i.e., the smaller the reduction, the larger the net return increase. One reason for this pattern is that smaller delivery reductions usually imply potentially larger consumptive use and yield increases, which tend to increase net returns. When farmers receive subsidies exclusively for upgrading to gated pipe with surge (scenario 4), net return increases are significantly lower than in the other scenarios. While consumptive use amounts are the same as in scenario 1, all of the delivery reductions need to be achieved with the relatively expensive gated pipe with surge. Even though the capital costs are largely or fully subsidized, net return increases are depressed due to the lower unit net incomes per acre for activities involving gated pipe with surge. Thus net return increases appear to be positively affected by the flexibility of a subsidy policy. Unit net return increases behave similarly to the net return increases and are by far the lowest in scenario 4.

[42] Interesting insights into distributional effects can be gained by comparing net return increases and subsidy costs across scenarios. In all cases, net return increases at the 20, 40, and 60% subsidy levels are predicted to be greater than total subsidy costs. At higher levels of subsidy, however, the total subsidy cost would become larger than the increase in

net return. At the 100% level, the cost to the public agency would range from 1.2 times the net return increase (in scenario 3) to an astonishing 4.3 times (in scenario 4). Similarly, unit net return increases are predicted to be higher than unit subsidy cost up to a subsidy level of 60% and lower at higher levels.

[43] To summarize, the model results indicate that in the case of a subsidy policy primarily intent on reducing deliveries (and drainage volumes), cost-sharing would be effective as long as the percentage is set high enough to induce a technology transition. Deliveries and drainage would be reduced, and the net return increases would be welcomed by farmers. However, cost-sharing involves an income redistribution from the public agency (and the taxpayer) to the agricultural sector and may not be feasible on a large scale in times of severe budget constraints. Incidentally, research examining options for reducing pollution from agricultural drainage suggests that when compared to a range of policy tools, cost-sharing may not be the most efficacious tool for improving water quality [*Wu et al.*, 1994].

[44] The model results also suggest that in the case of return flows being important for downstream water supplies, a reduction in deliveries from the adoption of improved irrigation technologies would result mainly in a redistribution of basin water and potentially harm water right holders dependent on return flows. Subsidy policies would not provide farmers with economic incentives to reduce consumptive use and thus are unlikely to make additional water available for alternative uses. In fact, consumptive use is likely to increase as a result of subsidies. Under realistic assumptions with regard to on-farm production, technology, and resource use choices, the model illustrates that the savings in water deliveries from improved technologies would allow farmers to increase the number of irrigations and/or apply water to additional land. If the possibility of upgrading to sprinklers were included in the modeling exercise, it could be shown that due to well-timed, uniform sprinkler irrigations farmers could also achieve higher yields as compared to equivalent amounts of surface irrigation water deliveries. Finally, farmers in the study area could informally market the "saved" water to other agricultural water users. All these responses are likely to increase consumptive use and lead to greater farm incomes but with negative impacts on downstream water users.

[45] Incidentally, in the situation of the New Cache La Poudre Irrigation Company, there is an opportunity for a subsidy policy to actually make additional water supplies available for other uses. Since the farmers with shares in the Colorado–Big Thompson project partly irrigate with water imported from another watershed, for which no limits to changes in use are provided under the Colorado prior appropriation system, they could use a subsidy policy to switch to more water efficient technologies and then sell the shares which they no longer need to the highest bidder. With the price of a share currently at about $12,000 per acre-foot, though, they would not depend on the provision of a public subsidy to make that transition.

6. Policy Implications

[46] The model results support earlier academic findings on irrigation technology transitions and water conservation. In particular, in river basins where return flows are not important to downstream water users, such as where return flows go directly to saline sinks or the sea, irrigation investments that reduce water deliveries can be considered as tools for conserving water for alternative uses. However, in cases where return flows have significant value, improved irrigation technologies only appear to produce additional water. They may redistribute water between stream and aquifer but are unlikely to decrease actual consumptive use. Furthermore, they may increase consumptive use if farmers can expand irrigated acreage.

[47] By explicitly incorporating the whole range of on-farm responses to public subsidies, including adopting a range of specific irrigation technologies, altering the crop mix and irrigated acreage, and, in particular, changing the number of irrigation events, this study extends the previous literature by demonstrating that a subsidy policy may actually increase consumptive use even without an expansion in irrigated acreage: that is, if it is profitable for farmers to use "conserved" water to apply additional irrigations to a crop. Whereas an extension of irrigated land beyond the original land to which a water right applies would not be permitted by Colorado's prior appropriation system, a change in irrigation scheduling would not violate its rules.

[48] The analysis also highlights the close relationship between water conservation in terms of water delivery reductions as a result of a switch to an improved irrigation technology, and the opportunity to conserve other inputs such as energy and labor. Only when the gains from energy and labor savings combined with potential yield increases outweigh the subsidized capital costs for irrigation investment, will it be profitable for farmers to switch to an improved irrigation system.

[49] Another important finding of the analysis is that the hydrologic, agronomic, and economic effects of irrigation investment subsidies depend on the design of the subsidy policy. By evaluating scenarios with alternative policy formulations and on-farm responses together with different levels of capital cost covered by the subsidy, the results indicate that the more on-farm responses are allowed for, the more likely it is that the increases in consumptive use and net returns are higher and reductions in water deliveries and return flows are lower. In addition, with higher subsidy levels (as long as they effect a technology transition), water delivery reductions and net return to water tend to be larger and return flows tend to be lower. However, the cost-effectiveness of the subsidy policy in terms of water delivery reductions would decrease concomitantly. As subsidy levels rise, larger amounts of public funds per acre-foot of delivery reduction would be required. While net return increases tend to be larger than total subsidy cost at lower subsidy levels, at higher subsidy levels total subsidy cost far outweigh the gains in agricultural net returns.

[50] These results have important implications for potential subsidy policies for water-conserving investments in the frequently encountered case of river basins where "wasted" water as return flow constitutes a considerable part of the downstream water supplies. Under all scenarios a subsidy approach would then be limited in its water conservation potential because it is unlikely to diminish consumptive use. This is because it does not provide any economic incentive to reduce the acreage irrigated, decrease the number of

irrigations, or switch to less water-consuming crops. As long as the irrigated area is not expanded accordingly, a subsidy policy would reduce water deliveries. Agricultural net returns to water are likely to rise whenever the subsidy policy induces the adoption of more water-efficient technologies. Even at low subsidy levels, though, just the cost of the subsidy (without considering administrative and other cost) to the public agency would almost be as high as the net return increases to farmers.

7. Concluding Remarks

[51] In light of the growing competition for limited water supplies in many parts of the western United States, many observers advocate a subsidy approach to encourage investments in water-conserving irrigation technologies as a means of making additional water available for rising urban and environmental demands and at the same time, preventing losses in agricultural production and income. On the basis of a combined crop simulation/linear programming model applied to the conditions experienced by a cooperative irrigation organization in Colorado's South Platte basin, this study adds to the previous literature by modeling in detail the potential farmer response to hypothetical subsidies for water-saving irrigation technologies and by explicitly assessing the hydrologic, agronomic, and economic effects of alternative cost-sharing levels.

[52] The model used in this study is based on a number of simplifying assumptions. Only a single period is considered. The irrigation organization faces an average weather year and typical irrigation water supplies. Farmers have precise water application control and knowledge about optimal timings of irrigation events. There is also no uncertainty about prices of inputs and outputs. Only surface irrigation technologies and one soil type are included. Improved irrigation technologies are predicted to be adopted as soon as the expected net return is greater than the one achieved with the former irrigation practice. Some of these assumptions could be relaxed in future work. The estimates of our model are nonetheless sufficient to suggest that for locations in many typical river basins, the various existing and proposed subsidy programs are at best ineffective in providing real water conservation.

[53] The model results also cast light on the controversy over the role and value of subsidy programs that encourage improved efficiency of irrigation water use. Adoption of measures that improve irrigation efficiency can increase crop production (by, for example, allowing more even coverage of fields), reduce labor and energy costs, positively influence farmer income, and thus provide an economic benefit to the rural communities where the program operates. From this perspective, subsidy programs for improved irrigation technologies are often seen in a very positive light. (This is especially true in localities where water supplies are relatively limited and/or highly variable.) From the broader national perspectives, though, where program funds have valuable alternative uses and added crop production may not be highly valued, such programs may be viewed as an expensive way to transfer income to farmers and rural communities.

[54] To achieve actual reductions of water consumption, conservation policies need to encourage reductions in the number of irrigations, switches to lower water consuming crops, and/or reductions in area irrigated. Municipal water suppliers and environmental groups wishing to obtain water for alternative, higher-valued purposes will be best served by a focus on purchasing consumptive use water rights.

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