Water conservation in irrigation can increase water use

Frank A. Ward[a,1] and Manuel Pulido-Velazquez[b]

[a]Department of Agricultural Economics and Agricultural Business, New Mexico State University, Las Cruces, NM 88003; and [b]Department of Hydraulic and Environmental Engineering–Institute of Water and Environmental Engineering, Universidad Politécnica de Valencia, Cami de Vera s/n 46120 Valencia, Spain

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Climate change, water supply limits, and continued population growth have intensified the search for measures to conserve water in irrigated agriculture, the world's largest water user. Policy measures that encourage adoption of water-conserving irrigation technologies are widely believed to make more water available for cities and the environment. However, little integrated analysis has been conducted to test this hypothesis. This article presents results of an integrated basin-scale analysis linking biophysical, hydrologic, agronomic, economic, policy, and institutional dimensions of the Upper Rio Grande Basin of North America. It analyzes a series of water conservation policies for their effect on water used in irrigation and on water conserved. In contrast to widely-held beliefs, our results show that water conservation subsidies are unlikely to reduce water use under conditions that occur in many river basins. Adoption of more efficient irrigation technologies reduces valuable return flows and limits aquifer recharge. Policies aimed at reducing water applications can actually increase water depletions. Achieving real water savings requires designing institutional, technical, and accounting measures that accurately track and economically reward reduced water depletions. Conservation programs that target reduced water diversions or applications provide no guarantee of saving water.

agriculture | sustainability | institutions | hydrology

Easterling (1) recently observed that a great challenge facing 21st-century political and scientific leaders will be to increase the world's food supply to accommodate a world growing to 10 billion or more people while also facing climate change. Water in the right quality, amount, time, and place is essential for ecosystems and for economies. Much of the world's food production depends on water for irrigation. Natural ecosystems are adapted to stream discharge, precipitation, and evaporation patterns. So, adjustments in the water cycle to climate, weather, and land-use change will have large and complex effects on economic and ecological systems

Many countries have inadequate water supplies to meet their current urban, environmental, and agricultural needs. In the face of increased water scarcity, population and water demands continue to grow (2, 3). The challenge is to grow enough food for 2 billion more people over the next 50 years while supplying growing urban and environmental needs for water (4, 5). Some analyses have estimated that 60% of added food required will come from irrigation (6). Raising food production to support this larger world population requires sustaining improved performance of irrigation (7–12).

As pressure mounts for irrigated agriculture to produce more crop per drop, there is a widespread belief in environmental and water policy circles that if irrigators made more efficient use of water then there would be more water for environmental uses and for cities (12, 13). More than a billion people worldwide lack safe affordable drinking water (8). A considerable number of informed individuals, large development organizations, and much popular belief subscribes to the view that measures to increase irrigation efficiency* will result in additional water for uses outside agriculture (16, 17). Numerous public policies have been implemented and billions of dollars in public and private investments spent to promote water conservation in irrigated agriculture. However, many of these investments have not made additional water available to new users. Although water conservation intentions carry considerable political weight, there is all too often little serious evidence on conservation outcomes that would be produced by water conservation programs in policy debates, funding opportunities, and the popular press. Moreover, studies that connect water use efficiency with wet† water savings are rare. Notable exceptions include the works of Hussain *et al.* (16), Huffaker and Whittlesey (17), Peterson and Ding (18), Huffaker and Whittlesey (19), and Schierling *et al.* (20).

This contribution of this article is to analyze agricultural water conservation subsidies with respect to their effect on water used in irrigation and on conserved water available for other uses. A basin-scale hydroeconomic optimization model is presented linking biophysical, hydrologic, agronomic, economic, policy, and institutional dimensions of the Upper Rio Grande Basin of North America (the Basin), shown in supporting information (SI) Fig. S1. Results of that model are used to examine farm income-maximizing choices regarding crop mix, irrigation technology, water demand, consumptive use, return flows, income, and taxpayer costs of a water-conserving program. The cost effectiveness of a range of conservation subsidy arrangements for reducing water depletions is also identified.

Materials and Methods

Water Conservation. Evapotranspiration (ET) from the watershed's surface is the depletion‡ or loss of water from a hydrologic basin associated with plant water use. Water diverted from its natural course through a canal, pipe, or other conveyance measure and applied in irrigation in excess of ET is not lost because it returns into the basin from which it was withdrawn via surface runoff or deep percolation. This water can be available to other users at other

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[1]To whom correspondence should be addressed. E-mail: fward@nmsu.edu.

*Many definitions of irrigation efficiency have been proposed (14, 15). For this article, efficiency is the ratio of water depleted by plant evapotranspiration (ET) to water diverted from the stream. ET is the consumed fraction of water diverted. As technologies or management practices are adopted that bring the ratio closer to 1, irrigation efficiency increases. Much of this article focuses on what happens to the nonconsumed fraction.

†The term wet water savings refers to real water compared with paper water, i.e. water rights.

‡Some writers prefer the term ''consumption'' to ''depletion,'' because depletion suggests the unsustainable action of drawing down on a stock (22). By contrast, consumption occur as a part of sustainable income. We use the term depletion because it contrasts with water diverted from the stream or water applied to the crop. Water diverted and water applied can return to a closed hydrologic basin. Depletion cannot.

Table 1. Crop water use, price, yield, and cost per acre, Lower Rio Grande, NM, 2006

Crop	Water applied*		ET*		Deep percolation*		Price		Yield, quantity/acre†		Production cost (0% capital drip irrigation subsidy), $/acre/year		Production cost (100% capital drip irrigation subsidy), $/acre/year‡	
	Flood	Drip	Flood	Drip	Flood	Drip	$/Unit	Yield units	Flood	Drip	Flood	Drip	Flood	Drip
Alfalfa	5.0	2.7	2.2	2.7	2.9	0.0	130.00	Tons	8.0	10.0	884	1,357	884	993
Pima cotton	2.8	1.5	1.2	1.5	1.6	0.0	1.05	Lbs	750.0	937.5	979	1,324	979	960
Upland cotton	2.8	1.5	1.2	1.5	1.6	0.0	0.75	Lbs	1,000.0	1250.0	1027	1,261	1027	897
Spring lettuce	2.5	1.4	1.1	1.4	1.4	0.0	5.84	Cartons	475.0	593.8	3001	4,398	3,001	4,034
Fall lettuce	3.3	1.8	1.4	1.8	1.9	0.0	6.23	Cartons	500.0	625.0	2,638	3,971	2,638	3,606
Fall onions	4.7	2.5	2.0	2.5	2.7	0.0	6.63	Sacks	1,200.0	1500.0	5,762	8,848	5,762	8,484
Midseason onions	4.0	2.9	2.3	2.9	1.7	0.0	6.38	Sacks	675.0	843.8	3,722	5,708	3,722	5,344
Spring onions	4.8	3.4	2.7	3.4	2.0	0.0	6.43	Sacks	825.0	1031.3	4,455	6,871	4,455	6,506
Grain sorghum	2.0	1.1	0.9	1.1	1.1	0.0	3.70	Cwt	40.0	50.0	615	728	615	364
Wheat	2.5	1.4	1.1	1.4	1.4	0.0	3.75	Cwt	92.0	115.0	718	929	718	565
Green chile	4.6	2.5	2.0	2.5	2.6	0.0	285.00	Tons	11.0	13.8	2,275	3,356	2,275	2,992
Red chile	5.0	2.7	2.2	2.7	2.9	0.0	0.72	Lbs	3,500.0	4,375.0	2,004	2,851	2,004	2,486
Pecans	6.0	3.2	2.6	3.2	3.4	0.0	2.28	Lbs	1,158.1	1,447.7	1,731	3,114	1,731	2,750

*Acre-feet per acre per year.

†Each crop is specified to have a linear relationship between water use (ET) and crop yield across irrigation technologies.

‡Includes annualized cost per acre of drip irrigation, operation, and maintenance.

times in other locations.§ One user's water inefficiency often serves as the source of another user's water supply.

On-farm adoption of drip irrigation is one measure widely believed to conserve water. Drip irrigation allows for precise application of water into plants' root zones, with little loss to runoff or deep percolation. A linear relationship is typical between ET and crop yield over a wide range of crops and water applications (21). So, irrigation technologies that apply water at optimal times and locations in plant root zones increase crop consumptive use of water and crop yield as irrigation efficiency increases. When yield goes up, ET typically rises.

Water losses through deep percolation or surface runoff will be reduced, possibly to nearly 0, through drip technology, but more ET will be used by the plant in supporting its reduced plant stress and higher yield. More efficient irrigation systems reduce diversions from streams and increase crop both yield and gross revenue (18). Depending on the cost of installing drip irrigation, costs and returns of production, and the price of water, the farmer who uses the technology may experience increased yield and higher income per unit of land. From the farmer's economic view the new water-conserving technology is good. However, basin-level consumptive use of water can increase.

Study Area. The Basin is that part of the area drained by the Rio Grande and its tributaries that flow from its headwaters to ≈70 miles south of the border cities of El Paso, TX and Ciudad Juárez, Mexico (Fig. S1). Surface water from the river meets the primary water needs of Albuquerque, NM, El Paso, and Juárez. In addition, it serves 1 million acres of irrigated land in the U.S. and Mexico. In fall 2004, water storage in Elephant Butte, the largest reservoir in the Basin, was <5% of capacity. After an unprecedented 25-year period of full-water supplies, water allocations during 2003 were reduced to just one-third of full-supply conditions.

Data. Table 1 shows the most important hydrologic, agronomic, and economic data for irrigated agriculture used by our analysis. Depending on the crop, water applied under drip irrigation is approximately half as much as under flood irrigation. However, crop ET is higher under drip irrigation, which reflects higher water depletions that support the typically greater yields experienced by irrigators who use this technology. ET under flood irrigation is typically less than half of water applied; the rest either seeps to deep percolation or returns to the stream as surface return flow. The table also shows that production costs per acre are typically much higher under drip than under flood irrigation, although that cost elevation is considerably reduced as the public subsidy of drip irrigation increases from 0 to 100%.

Modeling Framework. The hydroeconomic analysis developed for this article is a basin-scale accounting of the Basin's essential hydrologic relationships, institutions, and economic sectors. This integrated model is formulated as a mathematical optimization problem. The objective is the sum of net economic benefits¶ from basin water diversions, for off-stream uses, and for net benefits of water environments. The objective is to maximize the discounted value of net economic benefits over a 20-year time horizon. Constraints are used to characterize the basin's hydrology and its institutions. Our basin-scale approach extends similar previous work by Vaux and Howitt (24), Booker (25), and Hurd *et al.* (26), all of whom developed integrated basinwide hydrologic models for policy analysis containing an economic objective.

The model is formulated and solved on an annual time step, with reservoir storage and other hydrologic and economic conditions carried forward to each next time period. Fig. S2 shows a schematic of the basic hydrologic–agronomic balance at the field-stream level. Mathematical documentation of earlier versions of the model has been published elsewhere (27, 28). Although the model and its documentation were developed for the Basin, it was designed to be adaptable to other basins, cultures, and economic environments that characterize the economic value of water.

Hydrology. Basin hydrology is based on the principle of water mass balance, defined in both flows and stocks. The most important flows tracked by the model include headwater flows, streamflows at the basin's important stream gauges, water diverted, water applied to crops, water depleted, reservoir releases, groundwater pumping, seepage to aquifers, return flows to streams, reservoir evaporation, and reservoir releases. Important stocks include reservoir and aquifer levels. A hydrologic mass balance for both surface water and groundwater is enforced for all flows and stocks. The model includes major functions that influence any of the flows described above. The mass balance for reservoir stocks is given by starting storage minus reservoir releases plus river inflows to the reservoir minus evaporation. Changes in any period's groundwater stock are represented through effects of seepage, water applied, and water pumped.

Institutions. The U.S.–Mexico Treaty of 1906 is an important international treaty. Under it, the U.S. is obliged to deliver 60,000 acre-feet per year to Mexico at the El Paso–Ciudad Juárez border. Historically, in severe drought

§A fraction of water diverted in a basin may return to the basin too late, too far away, or in too low a quality to be of economical use or because the water flows into an irretrievable sink such as the ocean or saline lakes (23).

¶Excluded are costs associated with the public subsidy of drip irrigation's capital cost. From a national view, a public subsidy incurs opportunity costs because those resources typically have alternative uses.

periods, U.S. deliveries to Mexico have fallen below 60,000. Nevertheless, our model enforces a good-neighbor policy by requiring delivery of 60,000 acre-feet to Mexico in all conditions.

Various U.S. Federal laws affect use of the Basin's water. Our model enforces the Endangered Species Act of 1973 (ESA), which allocates the Basin's water to produce sufficient streamflow in the San Acacia reach of the Rio Grande (Fig. 1) to protect from extinction the endangered Rio Grande silvery minnow. The model enforces this constraint by requiring streamflows at the San Acacia gauge to exceed 240,000 acre-feet per year.

In the western U.S., numerous interstate compacts have been signed since 1922 signing of the Colorado River Compact. The Rio Grande Compact (the Compact), signed in 1938 by Colorado, New Mexico, and Texas, divides the river's annual flow among those states. It obliges each upstream state to make larger annual deliveries to the downstream state in wetter periods. Each state receives a specified percentage of headwater flows, so the Compact spreads the risk of drought or climate change among the three states. Our model allocates water among the states according to the Compact's written rules.

In many of the world's water-stressed regions, neighbors have agreed to share scarce supplies in drought periods. Since the early 1950s, the New Mexico and Texas have agreed to share water delivered by the Rio Grande Project. Based on historical agricultural acreage in production in southern New Mexico and Texas at the time of the Project's construction, U.S. lands in New Mexico receive up to 57% of any year's allocation, and lands in Texas have received up to 43%.

Economics. ***Benefits.*** The model's economic analysis accounts for both water use-related benefits and the benefits of a higher-quality water environment. Benefit functions were developed to approximate water users' willingness to pay for water-related services. The two urban water-use nodes in the model are Albuquerque and El Paso. For both of those cities, the value of water is measured by water's price times the number of units sold to its customers plus any related consumer surplus. Consumer surplus is measured as the area beneath the urban water demand function and above actual price charged. For environmental benefits, willingness to pay is measured as the maximum price that could be charged to visitors at the Basin's six major reservoir-based recreation sites.[‖] More details on the economics of urban and environmental values are presented in refs. 27 and 28.

Irrigation benefits. The agricultural analysis is based on estimating how income-optimized cropping practices adjust to various subsidies of drip irrigation. The agricultural analysis of water is based on estimating how acreage in production by crop and irrigation technology adjusts to various capital cost subsidy levels of drip irrigation, ranging from 0 to 100%. As is common worldwide, drip irrigation in the Basin is considerably more expensive than flood irrigation. It also requires less water applied per acre and produces greater crop yields. The answer to the question of whether or not drip irrigation is economically attractive to irrigators turns on what combination of economic and water supply conditions make it profitable to choose drip over flood irrigation.

Irrigators' choices are based on what provides the highest discounted net present value of farm income. Agronomic–economic data include price by crop, production cost and yields per acre by crop and irrigation technology, and total acres in production. The hydrologic relations included ET, water applied, deep percolation, and surface return flow per acre by crop and crop irrigation technology. The Basin's water supply is defined by average historical headwater flows as well as reservoir and aquifer starting conditions for 2006.

Other benefits. The basinwide model identifies water use patterns and water decisions that maximize discounted present value of net benefits. The model was designed to identify water use patterns that maximize the discounted net present value of economic benefits over water uses, locations, and time periods. Part of that total basin-scale net benefits includes farm income as described above. Gross benefits are defined for urban, agricultural, and environmental uses. Although the major focus of this article is the economics of water conservation in agriculture, the model views agriculture as only one of three water uses (29, 30).

Costs. *Production costs of irrigated agriculture.* Increased stream diversions or depletions typically require additional costs to be incurred to make suitable for human use the increased water used. For agricultural groundwater-pumping nodes, the largest incremental costs are those incurred for energy and for related operation, and maintenance. Costs are broken into variable and fixed costs, described below.

Variable costs vary with the scale of the irrigation enterprise (e.g., acres) and with the management decisions made, such as the type of field or irrigation technology chosen. They also vary with the intensity of any single input on a given land unit. Variable costs occur because of the decision to purchase additional inputs for use in production. In the long run, all costs are variable in the sense that given a long enough period, they can be varied. In the short run, such as a single year, revenues must exceed variable costs, or it is more profitable to cease production. Shutting down is always a choice for an irrigator facing growing water scarcity. At a point in time near the end of the irrigation season, nearly all costs are fixed in the sense that they have already been incurred, so the incremental revenue coming in from a crop is likely to be considerably higher than the additional variable costs needed to harvest the crop.

Other costs. For urban areas, there are considerable costs for purification to make the water safe and healthy for human consumption. Treatment costs are considerably higher than for agriculture, but urban treatment costs are typically lower for pumped water than for diverted river water. Urban delivery cost data were obtained from the Albuquerque and El Paso water utilities, and agricultural water cost data were obtained from published farm enterprise cost and return budgets. Both urban and environmental costs are included in the objective function as negative terms when costs are subtracted from benefits.

Net environmental benefits are measured as gross environmental benefits minus added gross environmental management costs needed to assure a higher quality environment. Data are scarce on costs of managing the water environment. As a first approximation, we measured those costs as management costs incurred by the New Mexico State Parks Department for maintaining fishing facilities and for supporting larger numbers of anglers in the face of reservoir volume increases.

Discounted net benefits. Discounted net present value is expressed in its standard algebraic form:

$$NPV = \sum_u \sum_t \frac{NBu_{ut}}{(1 + r_u)^t} + \sum_e \sum_t \frac{NBe_{et}}{(1 + r_e)^t} \qquad [1]$$

where the u and t indices refer to benefits and costs of water use and the water environment, respectively; r_u and r_e are rates for discounting water uses and water environments; and NB_{ut} and NB_{et} are net benefits from water uses and water environments. Water use in the Upper Basin is heavily constrained by scarce water supplies and by existing institutions. The four existing institutions described earlier are incorporated into the model. The discounted net present value includes the summed stream of net use-related benefits and net environmental benefits. Total basinwide economic benefits defined in this way are maximized subject to the constraints defined by hydrology and water allocation institutions described above. The objective as well as those water allocations and system operations that serve to maximize it are based on standard microeconomic welfare economics. Similar economic optimization models at the basin scale are described by Booker and Young (31), Draper *et al.* (32), Pulido-Velázquez *et al.* (33), and Booker *et al.* (34).

Solving the Model. We formulated the model as a dynamic nonlinear optimization model, for which the objective was to maximize discounted net present economic value summed over water uses, water environments, irrigation technologies, locations, and time periods. In the model, reservoir contents, pumping, water use patterns, and on-farm irrigation technologies are optimized over the model's time horizon, in which the hydrologic input is headwater inflows as well as starting values for reservoir and aquifer levels. The model accounts for physical interactions among uses (irrigation, urban, and environmental), storage (reservoirs and aquifers), flows (diversions, pumping, water applied, water depleted, and return flows), and losses (field, conveyance, and reservoir evaporation).

Results

Table 2 shows hydrologic impacts for the river, farm, and aquifer associated with various levels of public subsidies of drip irrigation. Impacts shown in the table are limited to the 89,000 acres served by the Elephant Butte Irrigation District (EBID) of southern New Mexico. The base case is defined by a policy of 0 subsidy. Under this scenario, farmers are predicted to apply 364,000 acre-feet, of which pumped groundwater supplies 91,000 acre-feet. Some acreage of all 13 crops shown in Table 1 enter the optimal solution under at least some of the public subsidy levels. For the base case, these include alfalfa on 18,760 acres,

[‖]Important excluded environmental values include benefits produced by instream flows at nonreservoir nodes and any environmental values, such as option, existence, or bequest values influenced by variations in reservoir levels or by other water decisions.

Table 2. Water conservation in irrigated agriculture for selected drip irrigation subsidies, Lower Rio Grande, NM, annual average, 2006–2025, hydrologic outcomes

		Hydrologic outcomes, 1,000 acre-feet/year									
		On farm				River					
Subsidy, % capital*	Subsidy, \$/acre/year†	Water applied	ET	Water Pumped	Reservoir release, inflow	Stream diversions	Surface return flow	Aquifer outflow (river gains if >0)	Downstream delivery (outflow)	Aquifer, change in storage	Total water conserved
0	0	364	167	91	555	273	0	32	314	74	0.0
10	36	371	171	86	566	285	0	34	315	80	−3.7
20	73	362	168	87	558	274	0	32	316	75	−0.6
30	109	328	176	56	555	272	0	29	312	67	−8.5
40	146	318	181	51	549	268	0	26	307	61	−13.6
50	182	318	187	52	533	267	0	24	290	56	−19.5
60	219	319	197	58	534	262	0	19	292	45	−29.6
70	255	324	203	66	532	258	0	17	291	39	−35.9
80	291	324	203	64	535	259	0	17	292	39	−36.0
90	328	324	203	69	513	255	0	15	273	36	−36.0
100	364	324	204	63	535	261	0	17	292	40	−36.7

*Total costs include Program Cost of Water Conservation subsidy.
†Total costs exclude Program Cost of Water Conservation subsidy.

pima cotton on 3,216 acres, upland cotton on 8,218 acres, fall lettuce on 4,467 acres, onions on 3,573 acres, wheat on 1,072 acres, green chile on 2,680 acres, red chile on 2,680 acres, and pecans on 25,906 acres. Under that base case, total optimized agricultural income is \$34.1 million per year. Under the optimal base case solution, flood irrigation is used for ≈90% of the service area in actual production with drip irrigation used for just <10%. This corresponds approximately to actual 2006 EBID conditions.

We identified effects of a range of cost-sharing arrangements by varying the proportion of the average annualized irrigation system improvement capital cost paid by the public agency versus the farmer. That part of capital cost paid by the public agency was parametrically increased from 0 to 100% in 10% increments.

Table 2 shows the hydrologic outcomes of 10 scenarios associated with alternative drip irrigation subsidy levels. The unconsumed part of irrigation water diverted from the stream is presumed fully available for other uses, either for downstream surface water use or as aquifer recharge that would be available for use in current or future periods. Drip irrigation produces higher ET than flood irrigation, while also producing higher crop yields. Raising the subsidy on drip irrigation induces more drip acreage and more total acreage into production when the Basin's reservoirs start very low as they were in early 2006. Total water applied (pumped plus diverted) falls from 364,000 acre-feet under the baseline to 324,000 under a 100% capital subsidy. Surface return flows are always 0. Groundwater pumping for irrigated agriculture falls considerably, from 91,000 under baseline to 63,000 under maximum subsidy. Aquifer-to-river gains fall from 32,000 acre-feet under baseline to 17,000 under the highest subsidy. Aquifer storage gains fall from 74,000 acre-feet under no subsidy to 40,000 under maximum subsidy. The net effect overall is greater water depletion (greater ET), which produces a negative conservation of ≈36,700 acre-feet per year under the highest subsidy compared with a defined 0 conservation with no subsidy. We find that a progressively increasing public subsidy of drip irrigation considerably reduces water applied to farmlands. However, it increases overall water use. These findings support the conclusions of Schierling *et al*. (20) as well similar findings published by Huffaker (35), Huffaker and Whittlesey (19), and Ahmad *et al.* (36). They also concur with the recent conclusions of Molden (37).

An important finding is that as the subsidy increases, water depletion never falls below base-level depletion. As the subsidy increases, the ratio of depletion to water diverted from the stream increases. The ratio of depletion to water diverted rises to 80% under a 100% subsidy from a base case of 61%, while water pumped is reduced from 91,000 acre-feet to 63,000 acre-feet.

Table 3 shows land use and economic outcomes produced by the same drip irrigation subsidy scenarios. Results show that as subsidy levels increase, net farm income increases from \$34.1 million under the base case to \$45.5 million under the highest subsidy. At the 100% subsidy, level drip irrigation is used for 46,000 of 87,000 acres in production, or 53%. Overall, results suggest that a water conservation subsidy policy is unlikely to reduce water depletions under any of the scenarios. In fact, water depletions, yields, and acreage are all predicted to increase if total water use is not constrained to base levels by the various water authorities. If total irrigated acreage is also allowed to increase, the potential increase in water depletions is even higher. We conclude that in river basins where downstream users and future generations depend on the unconsumed portion of diversions in the form of returns to the stream and raised aquifer storage, subsidies for conservation technology investments are unlikely to bring about a new supply of water but will likely lead to increased depletions.

Results of Table 3 show that subsidies do encourage a shift to more water-efficient technologies. By paying for a part of the capital cost, the program reduces farmers' irrigation costs. Because of reductions in water applied to crops, increased program subsidies also lead to savings in other variable costs, including energy and groundwater pumping. As the subsidy rises and as its implementation promotes a change in technology, results show continued reductions in water applied to crops. At the same time, net farm income increases because of the subsidy itself and because of the subsidy's impact on altered technology and increased crop yields.

Table 3 presents 5 indicators of total economic benefits in addition to farm income and program cost: These indicators include (*i*) net benefits of water use including costs of irrigation subsidies in total costs (national view); (*ii*) net benefits of water use excluding the irrigation subsidy cost (basin view); (*iii*) net benefits produced by the water environment; (*iv*) total net benefits of water use plus benefits of the water environment

Table 3. Water conservation in irrigated agriculture for selected drip irrigation subsidies, Lower Rio Grande, NM, annual average, 2006–2025; land use and economic outcomes

Land use outcomes (1,000 acres/year)					Economic outcomes ($1,000/year)						
Subsidy, % capital	Subsidy, $/acre/year	Land in drip irrigation	Land in flood irrigation	Total land under irrigation	Farm income	Program cost	Net benefits from water use A*	Net benefits from water use B†	Net benefits from water environment	Total net benefits A*	Total net benefits B†
0	0	7	68	75	34,102	0	519,848	519,848	23,273	543,121	543,121
10	36	8	69	77	34,723	309	520,211	520,519	22,465	542,676	542,985
20	73	9	66	76	34,770	690	519,826	520,517	23,204	543,030	543,720
30	109	25	52	77	35,242	2,794	518,190	520,984	23,253	541,443	544,238
40	146	32	47	79	36,219	4,613	517,348	521,961	23,313	540,661	545,274
50	182	36	45	81	37,499	6,475	516,686	523,161	22,877	539,564	546,038
60	219	42	42	84	38,903	9,185	515,514	524,699	22,807	538,322	547,506
70	255	45	42	87	40,473	11,422	514,848	526,269	22,821	537,668	549,090
80	291	45	42	87	42,171	13,131	514,836	527,968	22,775	537,612	550,743
90	328	45	42	87	43,632	14,773	515,446	530,219	23,046	538,492	553,265
100	364	46	42	87	45,506	16,571	514,663	531,234	22,795	537,458	554,029

*Total costs include Program Cost of Water Conservation subsidy.
†Total costs exclude Program Cost of Water Conservation subsidy.

including subsidy costs (national view); and (*v*) total net benefits of water use plus the water environment excluding subsidy costs (basin view). This last economic indicator is the objective function maximized for this analysis.

An important trend is the nearly uniform increase in the Basin's total net benefits with rising irrigation subsidies. Total net benefits from the Basin's view increase from about $0.543 billion per year with no subsidy to about $0.554 billion per year under a 100% subsidy, as farm incomes in the Basin increase from $34.1 million with no subsidy to $45.5 million with a 100% subsidy. From the national view, the story is different. Where the taxpayer's cost of the irrigation subsidy is included in total costs, national net benefits fall from a high of $0.543 billion with no subsidy to a low of $0.537 billion with a 100% subsidy. So, although the irrigation water conservation subsidy is economically good for the Basin, it is a weak economic performer for the nation.

Conclusions

Lubchenco (38) described a social contract between science and society, in which advances in science inform society's important decisions. Her observations certainly characterize the elusive search for policies that would stretch the world's effective supply of water by promoting water conservation in irrigated agriculture. Our findings from the Rio Grande Basin suggest that water conservation subsidies are unlikely to reduce water depletions by agriculture under conditions likely to occur in many river basins. These findings suggest that some programs subsidizing irrigation efficiency are likely to reduce water supplies available for downstream, environmental, and future uses. Although water applied to irrigated lands may fall, overall water depletions increase. Our findings suggest reexamining the belief widely held by donors that increased irrigation efficiency will relieve the world's water crisis.

The world's single biggest water problem is scarcity (13). Reducing wet water scarcity requires accurate measurement of water use at different scales, including better estimates of return flows and ET. It also requires defining water rights, water transfers, water use, and water accounting overall in water depletions rather than water applications. With better crops, higher yields, and more even distribution of water, our results show that resulting crop water depletions increase. For example, in recent years crop yields have increased dramatically in the upper part of the Basin in southern Colorado. Alfalfa, potato, and grain yields in this part of the Basin have increased considerably since the mid 1980s. Those increased yields coupled with changing irrigation practices have worked to increase overall water depletions.**

Our findings also suggest that where return flows are an important source of downstream water supply, reduced deliveries from the adoption of more efficient irrigation measures will redistribute the basin's water supply, which could impair existing water right holders who depend on that return flow. Our results indicate that water conservation subsidies will not provide farmers with economic incentives to reduce water depletions and therefore are unlikely to make new water available for alternative uses. In fact, depletions are likely to increase as a result of subsidies. Drip irrigation is important for many reasons, including greater water productivity and food security (12, 15), but does not necessarily save water when considered from a basin scale (37).

What measures can be taken to promote real water savings? A first step could be accurate accounting of basinwide water use. Water accounting analyzes use, depletion, and productivity of water at the basin scale (37). Accurate accounting and measurement of water use can help identify opportunities for water savings, increase water productivity, and improve the rationale for water allocation among uses (37). Other measures include reducing or converting nonbeneficial evaporation from soil or supply sources to beneficial crop ET, restricting acreage or water use expansion in cropped areas, switching to lower water-consuming crops, or irrigating current crops at a deficit (39, 40).

Careful definition and administration of water rights can play a role. Water rights, water markets, water transfers, and water accounting need to be defined in terms of water depleted, not just water applied. Without defining water use in terms of depletions, individual farmers who invest in more efficient irrigation systems recognize that they apply less water per acre. They may believe their water right is no longer fully used and may claim that the unused water is available for beneficial use. A common reaction among private irrigators and even among

**There are important cases where policies designed to reduce applied water successfully reduce depletions. These occur where irrigation return flows travel to a saline body such as the ocean, a saline lake, or brackish groundwater. In these cases, most applied water is consumptively used because unused irrigation water is lost for future freshwater use. Water-marketing efforts, such as those between southern California cities and California's Imperial Irrigation District, which drains into the saline Salton Sea, have successfully achieved water conservation in agriculture while providing incentives for more efficient water use in all sectors from both local private and regional social views. We thank an anonymous reviewer for this insight.

public water conservation program administrators is to create a new use of water or expand the current water use to a larger number of acres or to higher water-consuming crops. The U.S. National Resources Conservation Service Environmental Quality Incentives Program (41) revolves around the premise that if irrigators install a more efficient irrigation system and irrigate 2 parcels instead of 1 with the same water right, increased efficiency in water use results. Water rights administrators can guard against this error. Where water rights are administered based on water depletions, water right administrators will not permit investors in irrigation efficiency to presume that water is saved. Indeed, where hydrologic realities of a river basin are implemented into law, the right to acreage farmed and to water applied will be reduced after measures are taken to increase irrigation efficiency.

A major question for efficient public policy is whether or not the increase in net farm income compensates the forgone benefits of reduced return flows and seepage (12). This is a question facing water science, water policy, and water administration. Where reduced return flows and lost aquifer seepage block another's water use, conservation poses a serious question for water rights administration because those effects are often hard to measure and often occur with considerable delay. Answering this question requires sorting out conflicting impacts of water application versus water depletion and an understanding of the transmission of those effects at the basin scale.

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