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Analysis

Basin impacts of irrigation water conservation policy

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ABSTRACT

Climate change, uncertain future water supplies, growing population, and increased water demands continue to raise the importance of finding cost-effective water conservation measures. Irrigated agriculture is the world's largest water user, so governments, donor organizations, water suppliers, and farmers continue to look for measures that would produce more crop per drop. Despite the importance of promoting water conservation in agriculture, little work has been done that integrates hydrologic, economic, institutional, and policy dimensions of water conservation. This paper presents an integrated basin scale analysis of water conservation subsidies for irrigated agriculture. A dynamic, nonlinear programming model is developed and applied for the Upper Rio Grande Basin of Colorado, New Mexico, and Texas, USA. Several potential public subsidies of drip irrigation are analyzed for their economic and hydrologic impacts at both the farm and basin levels. Results indicate that water conservation subsidies for drip irrigation produce several effects. These include greater on-farm implementation of water-conserving technology, less water applied to crops, more water consumed by crops, increased farm income, greater crop production, more land irrigated, and increased total water-related economic benefits for the basin. Findings provide a framework for designing and implementing water conservation policies for irrigated agriculture.

1. Introduction

Political, scientific, and community leaders continue to face the challenge of increasing the world's food supply to accommodate a world growing to 10 billion or more while also confronting risks of a less reliable water supply in the face of climate change. A water problem exists where water is not supplied in the right quality, amount, time, or place. Much of the world's food production depends on water for irrigation (Doll and Siebert, 2000; Howell, 2001). Adjustments in the water cycle to climate, weather, and land use change will have large and complex effects on economic, ecological, cultural, and legal systems. The challenge is to grow enough food for 2 billion additional people over the next 50 years while supplying growing urban and environmental needs for water. Some analysts have estimated that 60% of additional food required will come from irrigated agriculture. Increasing food production to support this larger world population requires sustaining improved technical and economic performance of irrigation (Howell et al., 1998; Howell, 2001; Jackson et al., 2001; Lal, 2000; Wallace, 2000).

Growing demands placed on freshwater resources create a need to link economic and hydrologic research with improved water management and policy. Better monitoring, forecasting, and economic assessment of water resources can inform decisions on more efficient water allocations among competing uses (Jackson et al., 2001). Several recent studies have concluded that basin-wide analysis would considerably enhance the hydrologic and economic effectiveness of water conservation initiatives (e.g., Samani and Skaggs, 2008). Such analysis would save more water and save water at lower cost than would be the case without a basin-wide framework. Basin-wide analysis of water conservation measures is one way to guard against unexpected costs of a water-conserving measure that saves water at one location while reducing water available to downstream users or to future generations.

Water-conserving measures can contribute to sustainable agricultural policy (Aldy et al., 1998; Armstrong et al., 2000). Reducing the cost of water-conserving technologies like drip irrigation can be done through public subsidies. This provides important incentives for farmers to adopt water-conserving technologies, potentially increasing world food supplies and raising farm incomes. Use of drip irrigation has progressed from being a novelty employed by researchers to a widespread method of irrigation in water scarce environments for a range of both perennial and annual crops (Ayars et al., 1999; Camp, 1998).

Economic analysis of on-farm irrigation technology adoption is used to examine which water saving measures are economically viable for dealing with emerging water shortages. In particular, economic analysis of conservation technologies like drip irrigation is needed to understand irrigators' economic incentives to invest in sustainable measures to cope with growing water supply limits. Understanding their economic incentives predicts their water-conserving behavior.

Recent years have seen a large and wide-ranging research literature examining connections among crop water applied, crop

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water consumed, and crop yields. A short list of highly-cited examples includes Bailey and Spackman, 1996; Belder et al., 2004; Chaves and Oliveria, 2004; Fabeiro et al., 2001; Fereres and Soriano, 2007; Girona et al., 1993; Howell et al., 1998; Jones, 2000; Kimball et al., 1995; Kang et al., 2000; Kirda et al., 2004. Other important contributions include the works of Lamm et al., 1995; Moreno et al., 1996; Musick et al., 1994, and Oweis et al., 1998. Also, highly-cited work by Oweis et al., 2000; Wang et al., 2001; Zhang et al., 1999; Zhang and Oweis, 1999; Zhang et al., 1998a,b have contributed to our understanding of these important connections.

Worldwide, few basins see a more intense competition for water than what occurs routinely in North America's Rio Grande Basin. Water demands in this basin continue to increase in the face of growing population, increased importance of environmental water uses, and high levels of water use by irrigated agriculture. Numerous policy debates in this region center on ways to promote water conservation for agriculture. Examples include increased irrigation efficiency, subsidies of water-conserving measures, reduction of water-intensive crops, recycling and reuse, and water pricing reform.

Much of the research described above has produced impressive results. However, despite these accomplishments, few analyses of the impacts of agricultural water conservation policy have been conducted that explicitly integrate interacting elements of a basin's agronomy, hydrology, economics, and institutions. This paper attempts to take a first step in filling that gap. Its goal is to describe and present results of a decision support tool that fully integrates biological, physical, institutional, and economic impacts of a proposed policy that would subsidize on-farm investments in water conservation technology. It does so by developing, applying, and presenting results of a dynamic nonlinear programming model of the major competing uses of water in North America's Rio Grande Basin. The model is designed to identify hydrologic, land use, and economic impacts of several alternative potential public subsidies of the on-farm capital cost of drip irrigation. Results permit a comprehensive understanding of important interactions between agronomy, hydrology, institutions, and economics of a policy proposal that would promote on-farm investments of water conservation.

2. Methods of analysis

2.1. Study area

The Rio Grande Basin spans 180,000 square miles (0.38 square miles per square kilometer), including parts of three US states and five Mexican states. From its headwaters at 12,800 ft (3.28 ft per meter) at the Continental Divide in Colorado's Rio Grande National Forest, the river travels downstream for about 1800 miles (0.62 miles per kilometer) to the Gulf of Mexico. The basin's watershed is topographically and geologically diverse. Descending to the southeast from its headwaters, the Rio Grande mainstem is fed by several tributary streams and by the Closed Basin Project as it flows through the San Luis Valley of southern Colorado to support a large economy of irrigated agriculture. The river flows into New Mexico at the Lobatos stream gauge, then travels south to Taos, Espanola, Albuquerque, Socorro, and Las Cruces towards El Paso, Texas, where it begins to form the border between the US and Mexico. Several tributaries, principally the Rio Chama, Santa Fe River, Jemez River, Rio Puerco, Rio Salado, as well as snowmelt from the Sangre De Cristo Mountains feeding numerous small streams contribute to flows of the Rio Grande in New Mexico. It enters Texas, 23 miles north of El Paso at an elevation of 4000 ft, and continues downstream for 1250 miles, defining the US–Mexico border until it empties into the Gulf of Mexico. With an annual average discharge of about 1100 ft^3/s (35.31 ft^3/m^3) at the Otowi gauge near Espanola, New Mexico, the Rio Grande is not navigable by commercial shipping. It is limited to a native flow of 5% of the Colorado, 1% of the Mississippi, and one fiftieth of 1% of the Amazon.

Urban water demands are growing for the basin's three major cities: Albuquerque, New Mexico, El Paso, Texas, and Ciudad Juarez, Mexico. These demands have historically been met mostly by groundwater pumping. That pumping is not sustainable at current withdrawal rates. Albuquerque completed its surface water treatment plant in December 2008, and El Paso is increasing its use of surface water. As a result of the US Reclamation Act of 1902, the federal government financed and developed water supplies that encouraged settlement of the Rio Grande Basin by bringing considerable new acreage under irrigation, supported by cheap and reliable water supplies delivered to farmers.[1]

Compared to many of the world's other river basins, mountain snow pack and regional rainfall levels have always been low in the Rio Grande Basin, producing about 10 in. (0.3937 in. per centimeter) of precipitation annually averaged over the basin. Sustainable water management and conservation is important for the basin's future, especially in the face of rising populations, economic development, and from emerging environmental values of water.

Agriculture contributes only 5% of the basin's income, and is the largest water user.[2] In 2005, agricultural production accounted for about 12% of total employment for New Mexico, and irrigation uses about 90% of the basin's water. The current analysis is limited to the upper part of the basin shown in Fig. 1, ranging from the headwaters in southern Colorado to Fort Quitman, Texas (hereafter referred to as the Basin).

Beginning with the emergence of the environmental movement in the 1970s, considerable conflict among water users has resulted from growing environmental values and associated increased quantities of water assigned to securing or recovering a water environment. These conflicts have added complexity to policy choices in allocating water among demands for irrigated agriculture, endangered species protection, recreation, and urban water use. One important question whose answer can inform future policy debates centers around the economic effect of subsidies that would promote water conservation in irrigated agriculture to make more water available for urban and for environmental purposes.

Designing policies and institutions to promote water conservation can be productively informed through proper economic analysis; ignoring economic analysis risks well-intentioned policies conserving water at the cost of increased use of other scarce resources that have a greater value than the value of water saved.[3] Growing water supply scarcity increases the marginal value of the water for all users, so careful economic analyses of water-conserving options can inform the range of choices available to farmers to minimize overall economic losses produced by that scarcity.

2.2. Integrated basin tool

Growing interest in interacting effects of water policies has raised the visibility and importance of models to support improved decisions (e.g., Alcamo et al., 2003). For our analysis an integrated basin management tool is developed to comprehensively analyze the economics of an irrigation water conservation subsidy. A framework for testing alternative water policies was developed to account for the Basin's critical hydrologic relationships, institutions, and economic sectors.

The integrated model is formulated as a mathematical optimization problem, using the present value of total net economic benefits as the objective. Fig. 2 shows a schematic of the model's major elements. Constraints are used to characterize the Basin's hydrology and institutions. The analysis extends similar previous work by Vaux and

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[1] Irrigation in the region goes back long before the 20th century. For example, Europeans settled in what is now Dona Ana County, NM (Kirby, 1998) in the mid 19th century, expanding irrigation in the process. Some canals in the area have been dated to the 1600s.

[2] The basin's most important crops are barley, potatoes, alfalfa, lettuce, cotton, onions, sorghum, wheat, chile, and pecans.

[3] For example, the cost of additional capital and other resources needed to support drip irrigation is often higher than the economic value of water saved. This is an especially serious issue in developing countries like Afghanistan where capital is scarce or where associated resources like cheap energy are not available to support water conserving technology.

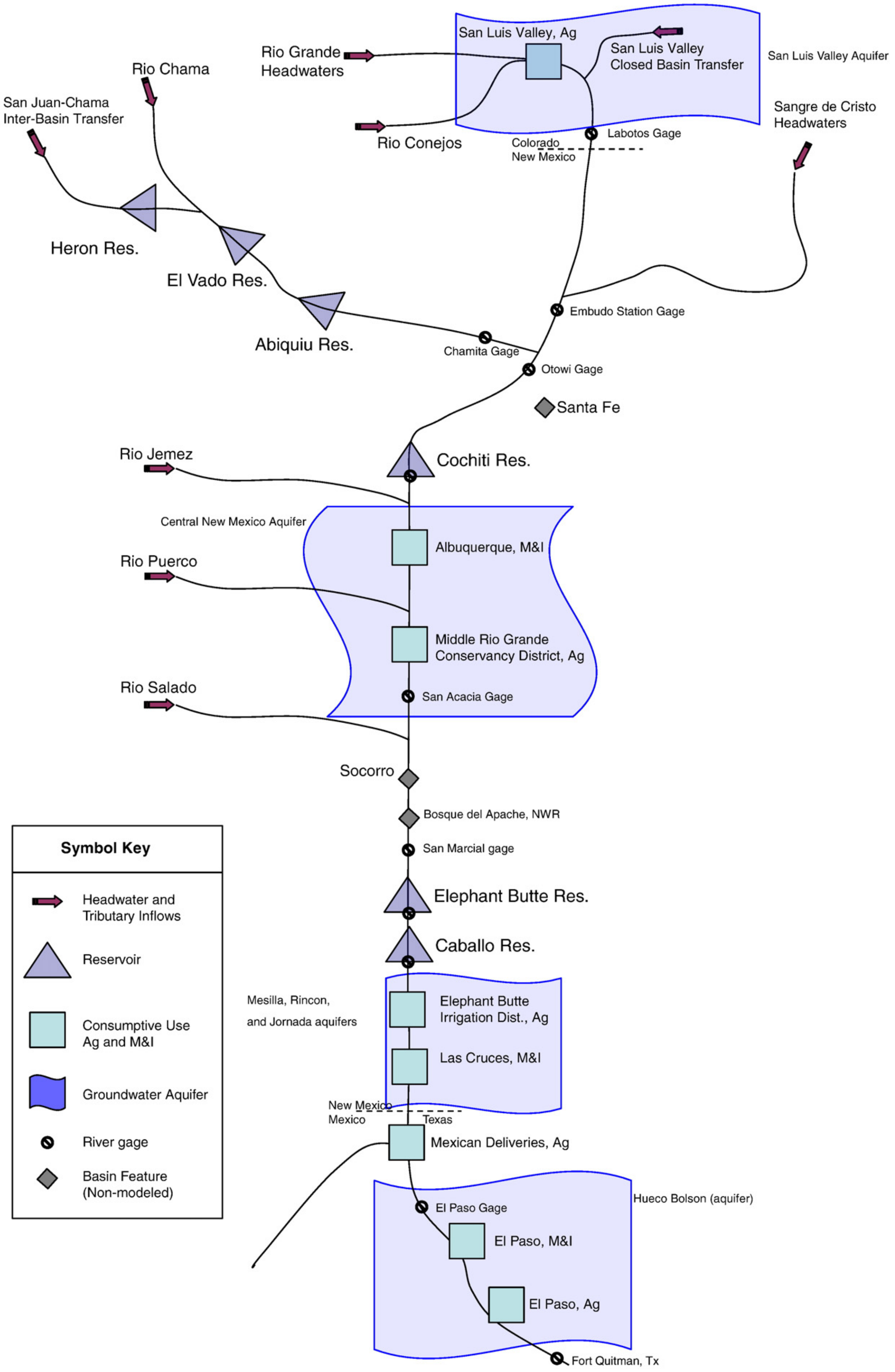

Fig. 1. Rio Grande Basin schematic.

Howitt (1984), Booker (1995), and Hurd et al. (2002, 2004) all of whom developed integrated basin-wide hydrologic models for policy analysis containing an economic objective. The model is formulated and solved on an annual time-step, with each year's reservoir contents and aquifer levels carried forward to the next year. While the model and its documentation were developed for the Basin, it was designed to be adaptable to the hydrology, culture, and economics of other basins.

2.2.1. Hydrology

The Basin has four major US agricultural producing areas (Fig. 1): they include the Rio Grande Water Conservation District in the San Luis Valley (SLV) of southern Colorado (http://www.rgwcd.org), the Middle Rio Grande Conservancy District (MRGCD) in central New Mexico (http://www.mrgcd.com), Elephant Butte Irrigation District (EBID) in southern New Mexico (http://www.ebid-nm.org), and the El Paso County Water Improvement District #1 (EP#1) in far west Texas (http://www.epcwid1.org). Each of these areas uses surface water for agricultural production; however, only SLV and EBID pump significant amounts of groundwater for irrigation. MRGCD and EP#1 have access to groundwater but neither has developed much groundwater pumping infrastructure for irrigation as of 2009. The Basin's two US urban water use areas in the model are Albuquerque, New Mexico (http://www.abcwua.org) and El Paso, Texas (http://www.epwu.org).

The Basin's hydrology is defined in both flows, consisting of streamflows, water use patterns, reservoir releases, as well as stocks for reservoirs and aquifers. A hydrologic mass balance, such as described by Ibanez et al., 1996, for surface water and groundwater is enforced for all flows and stocks.

Modeled flows include headwaters inflows (supplies), impacts of groundwater pumping on streams and aquifers, and net reservoir releases from storage, pumping from aquifers, irrigation and urban diversions, crop water ET,[4] aquifer recharge, groundwater flow to or from the river, surface water return flow to the river, and reservoir evaporation. The model includes major functions that influence streamflow at each node as well as impacts of each important activity upstream of that node. The mass balance for reservoirs is given by starting storage minus reservoir releases plus river inflows to the reservoir minus evaporation. For groundwater storage changes in any period, the stock of groundwater is represented through effects of current and past seepage, water applied to crops, and water pumped for irrigation and urban uses.

2.2.2. Economics

Economic analysis for the Basin's model is used to inform the water policy debates dealing with the effectiveness of water conservation subsidies for irrigated agriculture. Our analysis presents a “with versus without” comparison of a water conservation subsidy that would reduce producers' capital costs of investing in a drip irrigation system. A financial analysis of the costs and returns of producing irrigated crops is conducted in which the financial feasibility of flood versus drip irrigation is compared side by side.[5]

The integrated basin analysis is formulated as a mathematical optimization of the Basin's water allocations using the General Algebraic Modeling System (GAMS). The integration of economic, hydrologic, and institutional characteristics provides a mechanism for conducting analyses of various policy choices with complex impacts on the hydrology, agronomy, and economics of a river basin (e.g., Ward and Pulido-Velazquez, 2008; Gürlük and Ward, 2009).

The economic value of water in agriculture is measured by its contribution to producer net income. The value of urban uses is measured as revenue collected by the utility water supplier plus any unpriced consumer surplus. The economic value of the water environment is measured by the willingness to pay for water based recreation in the Basin's six major reservoirs, based on a regional travel cost model (Ward et al., 1997), updated with visitation data collected in 2003 at several New Mexico State Parks.

2.2.2.1. Enterprise budgets. Our economic analysis of irrigation rests on a foundation of farm level economics. The farm economics is analyzed thorough the use of enterprise budgets (e.g., Hawkes and Libbin, 2005). They summarize the economics of irrigated agriculture in the Basin, and are published by the respective three state land grant universities agricultural extension services: Colorado State University, New Mexico State University, and Texas A&M University. The budgets contain detailed financial information regarding flood-irrigated crop production, including crop acreage, equipment, crop production processes, and overall crop cost and return summaries.

The published budgets typically contain detailed financial data for agricultural production, typically based on flood irrigation, by far the most common irrigation technology used in the Basin. To inform the current analysis, the published base budgets applicable to EBID were adjusted to reflect crops produced under drip irrigation for EBID producers. The adjustments were based on a series of producer panel interviews held in fall 2006, in which a sample of EBID producers practicing drip irrigation were asked numerous detailed questions about impacts associated with the transition from flood to drip irrigation. For this analysis, differences between flood and drip irrigation for EBID producers were characterized to represent both hydrologic and economic impacts of drip irrigation and its various possible subsidies. Drip irrigation budgets for EBID were assembled that included data on yields, water use, labor requirements, accomplishment rates, equipment requirement, and system installation costs, all on a per acre basis.

At the producer panel meetings, one important difference found between flood and drip irrigation at the farm level was the cost and the risk involved in the investment of a drip irrigation system. Drip irrigation is expensive to install and requires specialized management practices. The drip irrigation budgets we developed reflect this difference by incorporating the additional equipment required, differences in purchased inputs, differences in labor requirements, and, of course, savings in water applications required. The economically-driven decision to invest in drip irrigation depends on current as well as expected future input and output prices and costs. Ultimately, there must be an economic advantage to drip irrigation to make it worthwhile to the producer. The enterprise budget approach permits a systematic incorporation of the economics of private on-farm decision making into the integrated basin model.

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[4] Our model accounts only for crop water evapotranspiration (ET). In future work we hope to account for ET consumed by non-crop riparian vegetation (e.g., Johnson, 1998). ET is the consumption of water from a hydrologic basin associated with plant water use. Water taken from its natural course and applied in irrigation in excess of ET may not be lost if it returns into the basin from which it was withdrawn by way of surface runoff or aquifer recharge. This water can be available to other users at other times in other locations. One user's water inefficiency can be the source of another user's water supply. On-farm adoption of drip irrigation allows for precise application of water into the plant root zones, with little loss to runoff or deep percolation. A linear relationship is typical measured between ET and crop yield over a wide range of crops and water applications. This means that irrigation technologies that apply water at the best times and locations in a plant's root zone can increase crop ET and crop yield. Higher yields are typically associated with higher ET. Water losses to aquifer recharge or surface runoff can be reduced to nearly zero through the use of drip technology, but additional ET will be consumed by the plant to produce higher yields (Perry, 2007; Ward and Pulido-Velazquez, 2008).

[5] Reduced water for agriculture resulting from competing demands, drought, or climate change may lead farmers to change their irrigation practices. Several adjustments are possible: changing the crop mix, idling land, deficit irrigation, and investing in water-conserving irrigation measures such as drip systems.

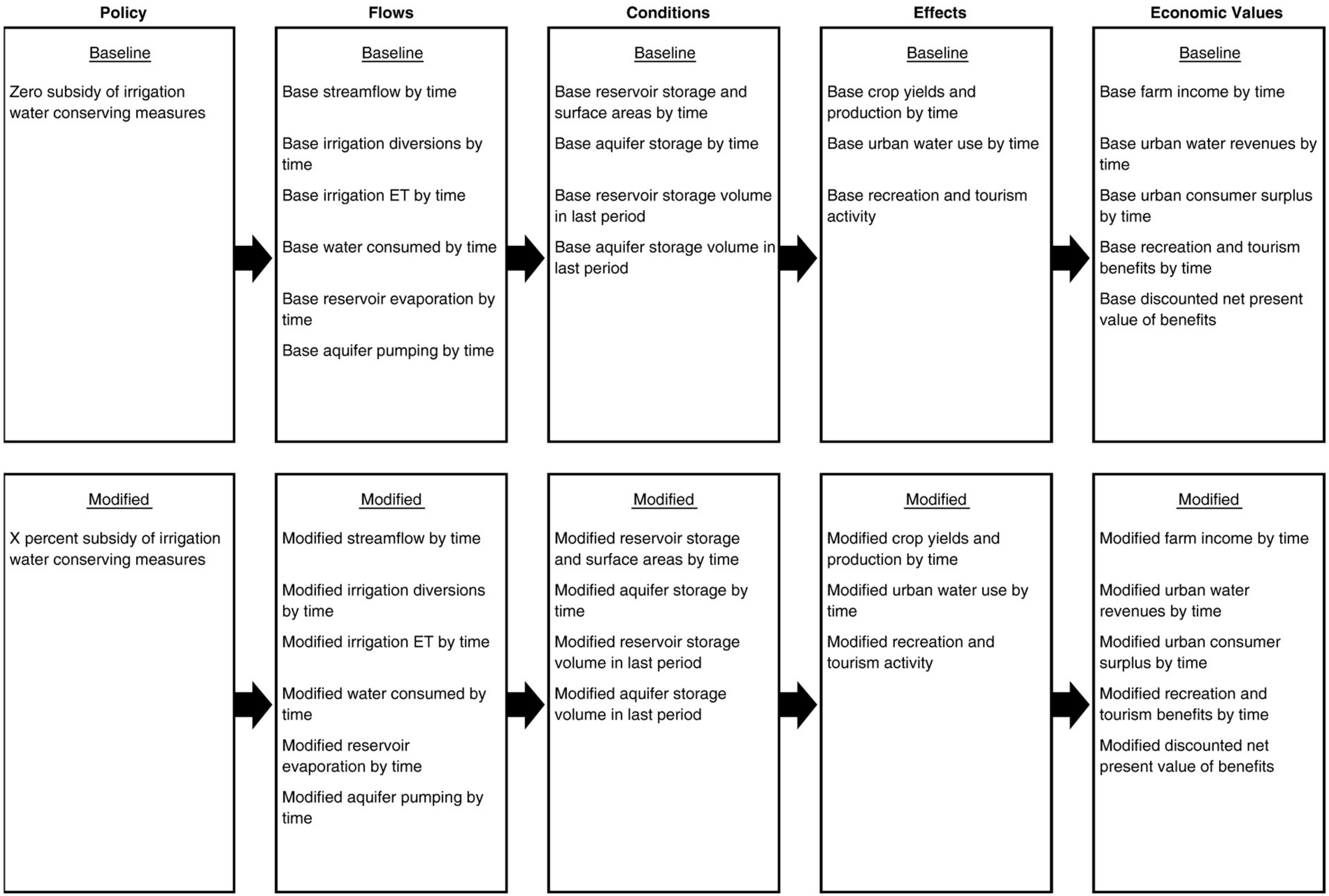

Fig. 2. Environmental policy analysis.

2.2.2.2. Model objective. The basin scale decision tool maximizes discounted net present value across all water uses, water environments, and time periods subject to hydrologic and institutional constraints described in more detail subsequently.[6] The objective is:

$$\mathrm{DNPV} = \sum_u \sum_t \frac{\mathrm{NB}_{ut}}{(1 + r_u)^t} + \sum_e \sum_t \frac{\mathrm{NB}_{et}}{(1 + r_e)^t} \tag{1}$$

where:

DNPV	discounted net present value
NB_{ut}	net use-related benefits for the uth water use node in the tth period
NB_{et}	net environmental benefits for the eth environment node in the tth period
u	use nodes (4 irrigation and 2 urban nodes)
e	water environment nodes (6 reservoir based recreation nodes)
t	time period
r_u	use-related discount rate (7.5%)
r_e	environmental discount rate (0%)

Discounted net present value is equal to the sum of use-related benefits and environmental benefits.

The model allocates water among the Basin's water uses and environments, locations, and time periods to maximize (1), subject to sustainability constraints in which all the Basin's aquifers and reservoirs are returned in the last year to at least their starting values in year one.

2.2.3. Institutions

Institutions are mechanisms of social order that govern the behavior of individuals to improve the welfare of the community. Institutions meet the needs of the community by establishing and enforcing rules governing individual behavior. There are several important water institutions that govern the behavior of water users in the Basin. These institutions in the form of laws, compacts, and treaties constrain proposals for reallocating scarce water resources in the Basin. Three such institutions stand out: first is the 1906 US–Mexico treaty (the Treaty). The Treaty promises 60,000 af (0.81 af per 1000 m^3) of water to Mexico every year to be delivered at the US/Mexico border near El Paso (IBWC, 1906), except in periods of extraordinary drought. In 1907, the Rio Grande Project (Project) described at http://en.wikipedia.org/wiki/Rio_Grande_Project, was authorized and determined the allocation of water out of Elephant Butte Reservoir to southern New Mexico, Texas and Mexico (King and Maitland, 2003).[7] Consistent with the Treaty, the model requires delivery of 60,000 af/year to Mexico.

A second important water institution in the Basin is the Rio Grande Compact (the Compact). In 1938 Colorado, New Mexico and Texas signed the Compact, which specified water allocations among the three US states of Colorado, New Mexico, and Texas (Hinderlider et al., 1938). In 1939, the Compact was approved by the US Congress. The decision support tool accounts for these three institutions as constraints that limit the Basin's allocation of water. Under the Compact, Colorado delivers water to New Mexico according to the native supplies produced in Colorado's headwaters. New Mexico is required to deliver flows to Texas at Elephant Butte Reservoir, for which the annual quantity of required deliveries is based on New Mexico's supplies, defined by annual native flows, measured at the Otowi gauge near Espanola, New Mexico, downstream of the confluence of the Rio Chama and Rio Grande. While not part of the Compact, up to 57% of US water released from the Rio Grande project is allocated to EBID irrigation, while up to 43% goes to EP#1, used for both irrigation and urban use as of 2009; this division is based on the historic irrigated lands in each district at the time of the signing of the Compact in 1938.[8]

A third important institution defining the allocation of the waters of the Rio Grande is based on the US federal listing of the Rio Grande Silvery Minnow (*Hybognathus amarus*) under the Endangered Species Act. This institution is integrated into the basin model by requiring a sustained annual streamflow of 50 ft^3/s to support the habitat of the listed fish, about 240,000 af of water per year measured at the San Acacia gauge in central New Mexico (Fig. 1). A 2003 Biological Opinion designated critical habitat and specifies different flow requirements based on whether the year is categorized as dry, average or wet, using measurements taken at the Otowi gauge in May (US DOI, 2003).

2.3. Defining water conservation

Historically, the need for water conservation has received less attention than the need for adequate water use. In fact in 2002, the United Nations formally declared that all have a human right to water. Under that declaration, the right entitles everyone to sufficient, safe, acceptable, physically accessible and affordable water for personal and domestic uses. Many communities have invested heavily over many years to make sure water is available, accessible, and cheap. For all its recent interest, there have been few debates over the definition of water conservation. So the definition proposed by wikipedia at *http://wiki/wiki/Water_conservation* may be typical: “Water conservation refers to reducing the use of water and reducing the waste of water.” Unfortunately, with growing water scarcity and the need to deal with it effectively, this definition helps little in the search for cost-effective water conservation programs.

One way to target cost-effective water conservation programs could be to add an economic dimension to what conservation policies aim for. With that in mind one economic definition of water conservation is any reduction in water use for which economic benefits exceed economic costs (Ward et al., 2007).

For an irrigation management practice to be considered economically conserving, it must save water through reduced consumption while producing a net increase in aggregate economic welfare. Using this criterion, a proposed water conservation program will avoid saving low-valued water at the cost of other higher-valued resources. Identifying water-conserving programs defined in this way can inform policymakers in the search for economically performing water conservation decisions (Young and Haveman, 1985). The basin-wide approach used for this study offers considerable insights into discovering economically effective water-conserving policies. Similarly, Samani and Skaggs (2008) describe several misconceptions surrounding water conservation for irrigated agriculture.

Drip irrigation applies small amounts of water to the crop's root zone at a slow but steady rate. In the Basin, where it is practiced, drip tapes distribute the water and are typically buried to a depth of 8–10 in. below the surface in order to reach the crop root zones. The close interaction between the root zone and water source allows the irrigator to divert less water from the stream and apply less water to a given field than is normally applied under flood irrigation. With specialized design, proper installation, and careful management,

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[6] Maximizing the discounted net present value of total benefits through optimized water allocations simulates a competitive market for water. There is a very large literature on water markets (e.g., Bauer, 1997; Weinberg, et al., 1993).

[7] That project is described in more detail at http://www.usbr.gov/dataweb/html/riogrande.html.

[8] In 2008, a new operating agreement for the Rio Grande Project brokered by NMSU civil engineering professor Phil King, was signed. The agreement provides for increased storage by Texas of carryover water, up to 60% of each year's full allocation, in Elephant Butte Reservoir. It also provides for increased groundwater pumping in drought periods by New Mexico. Both states got what they wanted, and each state gave up less in value than what they got in return.

Table 1
Land and water use patterns, Rio Grande Basin, USA, annual average, 2006–2025.

Subsidy (% capital)	Subsidy ($/ac/year)	Irrigated Area								Urban Area			
		Rio Grande Conservancy District		Middle Rio Grande Conservancy District		Elephant Butte Irrigation District		El Paso County Water Improvement District		Albuquerque		El Paso	
		CO		NM		NM		TX		NM		TX	
		Land (1000 ac/year)	Diversions (1000 af/year)	Land (1000 ac/year)	Diversions (1000 af/year)	Land (1000 ac/year)	Diversions (1000 af/year)	Land (ac/year)	Diversions (1000 af/year)	Households (1000s)	Diversions (1000s af/year)	Households (1000s)	Diversions (1000s af/year)
30	0	268.1	821.3	45.0	153.9	85.7	376.2	37.1	130.9	107	135.7	121	172.8
10	36	268.1	821.3	45.0	153.9	86.5	377.8	37.1	130.9	107	135.7	121	172.8
20	73	268.1	821.3	45.0	153.9	86.5	377.8	37.1	130.9	107	135.7	121	172.8
30	109	268.1	821.3	45.0	153.9	86.5	368.3	37.1	130.9	107	135.7	121	172.8
40	146	268.1	821.3	45.0	153.9	86.5	323.5	37.1	130.9	107	135.7	121	172.8
50	182	268.1	821.3	45.0	153.9	87.3	314.9	37.1	130.9	107	135.7	121	172.8
60	219	268.1	821.3	45.0	153.9	88.3	304.0	37.1	130.9	107	135.7	121	172.8
70	255	268.1	821.3	45.0	153.9	89.3	304.5	37.1	130.8	107	135.6	121	172.7
80	291	268.1	821.3	45.0	153.9	89.3	304.3	37.1	130.8	107	135.6	121	172.7
90	328	268.1	821.3	45.0	153.9	89.3	304.0	37.1	130.9	107	135.7	121	172.8
100	364	268.1	821.3	45.0	153.9	89.3	296.5	37.1	130.9	107	135.7	121	172.8

agricultural producers may receive the benefits of higher yields, more efficient water use, and labor savings.[9]

The use of a drip irrigation system makes no guarantee of reduced crop ET. A crop's water requirement does not change with the use of drip irrigation. However, higher yields are possible when the drip irrigator avoids deficit irrigation. Drip irrigation supplies water directly to the root zone, increasing the percentage of applied water that reaches the plant, typically increasing yields (Clothier and Green, 1994). In the EBID area, deficit irrigation with flood irrigation technology is a common practice, especially in drought years. Under the practice of deficit irrigation, farmers apply less water to the crop than what's required for maximum yields as one strategy to minimize economic losses associated with water shortfalls.

One barrier to the adoption of drip irrigation in the EBID service area is the high capital cost of implementing the change from a flood to drip irrigation system. At the producer panel sessions, we discovered that most EBID producers who had changed from flood to drip irrigation were motivated not by the desire to conserve water, but to achieve higher yields and reduced non-water operation costs.[10]

2.4. Water conservation subsidies

Installation costs for drip irrigation systems are amortized based on the total cost of the system, system life, and the interest rate. For this analysis, the cost used is $2500 per acre (2.47 ac/ha) for a system that has an expected life of ten years with an interest rate of 7.5%. Amortizing produces an annual payment amount that accounts for the life of the loan, total capital cost, and interest. The following amortization was used to translate capital into annual equivalent costs of investing in a drip irrigation system:

$$\mathrm{AP} = \frac{i[\mathrm{CC}]}{1-(1+i)^{-T}} \tag{2}$$

where:

AP	annual equivalent amortization payment = $364
CC	unsubsidized drip irrigation system capital cost/acre = $2500
i	interest rate = 7.5%
T	system life = 10 years

The resulting annual equivalent cost was $364 per acre for the case of zero capital subsidy for EBID producers. With no water conservation subsidy, total undiscounted installation cost per acre summed over the 10 year system life is $3640. This sizeable investment is the cost that a public water conservation subsidy aims to reduce. This amortization formula was adjusted to account for the reduced capital cost associated with various increases in the public subsidy.

3. Results

Results are shown for eleven model runs, in which the drip irrigation subsidy for EBID producers was varied from 0% to 100%, in 10% increments. For each run, water and water uses were allocated throughout the Basin in such a way as to maximize discounted net present value of summed water uses and water environments.

3.1. Land and water use

Table 1 shows land and water use patterns for the Basin under the 11 possible drip irrigation subsidies for EBID producers. An important pattern revealed is that total land in crop production uniformly increases with a larger percentage capital subsidy, increasing from a low of 85,700 EBID acres in production at no subsidy to 89,300 ac in production at a 100% subsidy.[11] Water withdrawals for irrigation applied to EBID crops decrease nearly uniformly with a growing drip irrigation subsidy, from a high of 376,200 af/year[12] for EBID crops to a low of 296,500 af with a 100% subsidy.

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[9] Drip irrigation systems in EBID typically require field flushing of accumulated salts once per growing season, usually performed at the end of the growing season. This is an important best management practice (BMP) needed to reduce any salinity levels within the soil, which also incurs the additional cost of finding the water for the flush. Flood irrigation provided the flush during the normal course of irrigation; drip irrigation systems do not experience flushing because irrigation water applications are emitted slowly and intermittently to the root zone of the crop through the distribution system. An excellent drip irrigation web site is http://www.icid.org/index_e.html.

[10] Drip irrigation systems are expensive to install. Lacking a considerable public subsidy, these systems are believed by many Basin producers to reduce incomes in conditions where both surface and groundwater are cheap and reliably supplied. However the attractiveness of drip irrigation increases where water is expensive or unreliable. Considerably more private investment in drip irrigation has occurred in areas outside the EBID service area that lack access to surface water where groundwater depths can exceed 450 ft.

[11] Table 1 shows that the existing EBID land in production is just under 20% of the irrigated land for the Basin. So the increased land in production in EBID induced by the subsidy is just under 2% of the entire Basin's irrigated area.

[12] Acre feet per year are abbreviated as af/year in Table 1.

Table 2
Land in irrigated agriculture for selected drip irrigation subsidies, lower Rio Grande, NM, USA, annual average, 2006–2025.

Subsidy	Subsidy	Land in drip irrigation	Land in flood irrigation	Total land under irrigation
(% of capital cost)	($/ac/year)	1000 ac/year		
80	0	19.8	65.9	85.7
10	36	20.8	65.6	86.5
20	73	20.8	65.6	86.5
30	109	28.3	58.2	86.5
40	146	49.3	37.2	86.5
50	182	54.6	32.7	87.3
60	219	60.9	27.4	88.3
70	255	62.8	26.5	89.3
80	291	63.0	26.3	89.3
90	328	63.3	26.0	89.3
100	364	66.1	23.2	89.3

3.2. Land use by irrigation technology and conservation subsidy

Table 2 presents results of total EBID land under irrigation for both flood and drip irrigation technologies and for each of the drip irrigation subsidy levels. The pattern shown in the table is clear: farmland in production under drip irrigation shows a uniform increase with an increased conservation subsidy, ranging from a low of 19,800 ac drip irrigated with no subsidy to a high of 66,100 ac drip irrigated with the maximum drip subsidy. Similarly, acreage flood-irrigated falls from a high of 65,900 ac with no drip subsidy to a low of 23,200 at the maximum drip subsidy. Total acreage summed over both flood and drip technologies uniformly increases as the subsidy increases: from 85,700 ac with no subsidy to a maximum of 89,300 with the highest subsidy. While not shown in the table, the total gross economic value of crop production in the Basin increases by an impressive 10% from an average of $337.0 million per year without a drip subsidy to an average of $371.5 million per year with the highest subsidy, because of impacts of drip irrigation on increased crop yields. So an important outcome of the subsidy is to produce a shift in acreage from flood to drip irrigation as well as bringing forth a higher gross economic value of food production with the Basin's available water.

3.3. Crop water applied

Table 3 shows the water applied to irrigation for EBID by crop irrigation technology, crop, and drip irrigation subsidy level. Three important patterns are evident: (1) reduced water applications under flood irrigation with a rising drip subsidy, (2) increasing quantities of water applied under drip irrigation with the rising drip subsidy, and (3) reduced overall water applied with the rising drip subsidy.

Alfalfa tells a major part of the story. It applies 41% of total flood-irrigated water at EBID with no drip irrigation subsidy, at 134,000 af compared to 325,400 af total water applied to all crops with flood technology. Moreover, drip irrigated alfalfa is nearly economically viable with no subsidy at all. Small amounts of alfalfa acreage enter the mix as the flood-drip threshold is crossed from a 30% to 40% subsidy.[13] At the point when the drip irrigation subsidy increases to 50%, 72,000 af of water are applied to alfalfa entirely under drip irrigation compared to 134,000 af applied under flood irrigation with no subsidy. Compared to total EBID water applied at just over 376,000 af annually without a subsidy, about 297,000 af/year are applied with the maximum subsidy. The result is a water application savings of just under 80,000 af produced by the maximum subsidy.

3.4. Crop water consumed

Table 4 presents results of crop water consumption. It focuses on crop water ET, water consumed by the plant.[14] Crop water ET is lost to any future water use in the Basin. That ET lost is a basin level measure of net water use. Table 4 shows total EBID irrigation water consumed by irrigation technology, crop, and drip irrigation subsidy level. Three important patterns are revealed as a response to a growing drip subsidy: (1) reduced water consumption under flood irrigation, (2) increased water consumption by drip irrigation, and (3) increased overall water consumption.

The overall effect of a rising drip subsidy is greater water consumption, producing a negative conservation of 26,300 af/year under the highest subsidy compared to zero conservation defined by no subsidy. Recall that Table 3 table shows a progressively increasing public subsidy of drip irrigation reducing water applied to irrigation. By contrast, Table 4 shows that the same subsidy increases overall water consumption. Taken together, the two tables show that with an increased subsidy, water consumption, growing to 217,000 af/year under the maximum subsidy, never falls below base-level consumption of 190,700 af/year consumed with no subsidy. As the subsidy increases, the ratio of depletion to water diverted from the stream increases. The ratio of depletion to diversion rises to 73% under a 100% drip subsidy from a base case of low of only 51%, with a considerably higher amount of water recharging to the aquifer without a drip subsidy.

3.5. Farm income

Table 5 shows average annual farm income by crop, technology, and conservation subsidy for EBID producers. The table reveals two patterns in the face of a higher drip subsidy: (1) increased farm income and (2) some crops more favored than others.

In total, EBID farmers find the drip irrigation subsidy attractive economically, increasing the district's farm income by 29%, from a base average of $46.8 million per year with no subsidy to an average of $60.6 million per year with the maximum subsidy. Income from alfalfa production is especially favored by the subsidy. Alfalfa income ranges from a base of $10.4 million in income under flood irrigation with zero income earned in drip irrigation to a maximum of $13.8 million earned under drip irrigation with zero earned under flood irrigation under the maximum subsidy. Interestingly, pecan production shows little economic gain produced by the drip irrigation subsidy, partly because the water price charged to EBID irrigators is low combined with a high annual operation cost of drip irrigation for the district's pecan growers.

3.6. Basin-wide economic benefits

Table 6 considers the entire Basin. It shows the Basin's total economic benefits for all three major stakeholders: agriculture, urban, and environment. The top part of the table shows benefits produced by water use by cities and farms. The lower part of the table shows recreation benefits produced by the water environment, which for the

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[13] Our findings are consistent with a recent report on economic success in Arizona for drip-irrigated alfalfa, described at http://westernfarmpress.com/alfalfa/drip-irrigation 0518. The Arizona family recently started growing alfalfa with a drip irrigation system. They had historically grown cotton and wheat under drip, but until lately, had not grown alfalfa because of its weaker price and profitability. With recently increased hay prices, the family planted drip-irrigated alfalfa. Consistent with the findings of our study, they found that drip-irrigated alfalfa conserves water and increases yields. The farm uses about one-third less water to grow alfalfa with drip irrigation compared to the more common flood irrigation.

[14] For practical purposes, all water applied to the crop under drip irrigation is consumed by the crop, whereas under flood irrigation, only about half of crop water applied is consumed by plant ET. More details are in Ward and Pulido-Velazquez (2008).

Table 3
Irrigation water applied by crop, technology, and water conservation subsidy, lower Rio Grande, NM, USA, annual average, 1000 af/year, 2006–2025.

Crop	Irrigation technology	Water conservation subsidy (percentage of capital cost)										
		0	10	20	30	40	50	60	70	80	90	100
Alfalfa	Flood	134.0	134.0	134.0	134.0	46.9	26.8	0.0	0.0	0.0	0.0	0.0
Pima cotton	Flood	8.8	8.8	8.8	3.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Upland cotton	Flood	22.6	22.6	22.6	7.9	1.1	0.0	0.0	0.0	0.0	0.0	0.0
Spring lettuce	Flood	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Fall lettuce	Flood	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Fall onions	Flood	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Mid season onions	Flood	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Spring onions	Flood	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Grain sorghum	Flood	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.2	0.0
Wheat	Flood	2.7	2.7	2.7	2.7	2.7	2.7	2.7	0.5	0.0	0.0	0.0
Green chile	Flood	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Red chile	Flood	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pecans	Flood	155.4	155.4	155.4	155.4	155.4	155.4	155.4	155.4	155.4	155.4	139.4
Alfalfa	Drip	0.0	0.0	0.0	0.0	46.8	57.6	72.0	72.0	72.0	72.0	72.0
Pima cotton	Drip	0.0	0.0	0.0	3.1	4.7	6.0	7.5	9.0	9.0	9.0	9.0
Upland cotton	Drip	0.0	0.0	0.0	7.9	11.5	12.1	12.1	12.1	12.1	12.1	12.1
Spring lettuce	Drip	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Fall lettuce	Drip	7.6	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
Fall onions	Drip	8.9	8.9	8.9	8.9	8.9	8.9	8.9	8.9	8.9	8.9	8.9
Mid season onions	Drip	8.1	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2
Spring onions	Drip	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1
Grain sorghum	Drip	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.4
Wheat	Drip	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.2	1.4	1.4	1.4
Green chile	Drip	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6
Red chile	Drip	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2
Pecans	Drip	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.6
Total applied	Flood	325.4	324.4	324.4	303.9	206.9	185.7	158.9	156.8	156.2	155.6	139.4
Total applied	Drip	50.8	53.4	53.4	64.4	116.5	129.2	145.1	147.7	148.0	148.3	157.0
Grand total	Total	376.2	377.8	377.8	368.3	323.5	314.9	304.0	304.5	304.3	304.0	296.5
Change in water applications (ref, no subsidy)	Total	0.0	1.6	1.6	−7.9	−52.7	−61.3	−72.2	−71.7	−71.9	−72.2	−79.7

current analysis is limited to water based recreation at the Basin's six major reservoirs.[15]

The table reveals several important patterns: (1) considerable growth in economic benefits from irrigated agriculture at EBID with increasing levels of the drip irrigation subsidy; (2) little effect on other urban or farming benefits in the Basin; (3) increases in recreation benefits with a growing drip irrigation subsidy brought on the higher reservoir levels needed to supply additional water to EBID irrigators produced by higher crop ET; (4) a much higher economic value of water for urban uses than irrigation: urban use contributes about 86% of the Basin's total economic value of water uses under a zero conservation subsidy; and (5) total economic benefits from water summed over uses and environments increase in the face of a growing drip irrigation subsidy. Those total benefits increase from a low of about $669 million with no conservation subsidy to a high of about $684 million at a 100% subsidy. So, even though crop water ET increases total water consumption in the face of a growing drip irrigation subsidy, the Basin is better off as a whole economically by about $15 million with the highest drip irrigation subsidy.

3.7. Reservoir storage

Table 7 shows reservoir storage levels for each of the Basin's six major reservoirs by water conservation subsidy level. Results are entirely compatible with findings shown in the previous tables: Elephant Butte Reservoir, the source of water supply for EBID, holds more water to meet the increased water consumption demands associated with greater crop water ET. This higher crop water ET with a higher conservation subsidy occurs because of the progressively higher crop yields brought about by EBID farmers taking advantage of the growing subsidy. Average annual reservoir storage levels over the 20 year period of analysis increase from 1.473 million acre feet to 1.701 million acre feet at that reservoir.

Other reservoirs in the Basin show a more limited response in increased reservoir storage in the face of a higher conservation subsidy. However, Abiquiu Reservoir increases from a low annual average of 603,000 af with no subsidy to a much higher storage volume of 902,000 af under the maximum subsidy.[16] Heron Reservoir near the Colorado–New Mexico State line also plays a part in supporting these increased irrigation water demands, increasing from an average of 268,000 af under the base subsidy to a high of 316,000 under the highest subsidy level. These findings reveal the important truth that a system of several water storage facilities can share the burdens of water consumption needs brought on by a policy. A larger number of water storage facilities available to support the requirements of a policy reduces the demands imposed on any single water storage facility.[17]

3.8. Total water consumed

Table 8 shows results of total water consumption throughout the Basin by conservation subsidy. Results are split by beneficial use and by reservoir evaporation. Four important patterns are revealed: (1) water consumption from EBID agriculture increases with the level of the conservation subsidy, (2) other agricultural areas' water use is only affected slightly by the subsidy (3) water consumption from urban use is virtually unaffected by the subsidy, and (4) reservoir evaporation increases considerably with the level of the subsidy. The first three results

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[15] Our analysis does not account for important environmental values of instream flows, water-related endangered species habitat, and option, existence, or bequest values of improving the surface or groundwater environment.

[16] Maximum capacity at Abiquiu Reservoir is 1.5 million acre-feet. The reservoir is described at http://pubs.usgs.gov/sir/2004/5188/pdf/sir2004-5188.pdf.

[17] Our findings emphasize the importance and value of integrated models of an entire river basin as a way to comprehensively inform water policies.

Table 4
Irrigation water consumption by crop, technology, and conservation subsidy, lower Rio Grande, NM, USA, annual average, 1000 af/year, 2006–2025.

Crop	Irrigation technology	Water conservation subsidy (percentage of capital cost)										
		0	10	20	30	40	50	60	70	80	90	100
Alfalfa	Flood	57.6	57.6	57.6	57.6	20.2	11.5	0.0	0.0	0.0	0.0	0.0
Pima cotton	Flood	3.8	3.8	3.8	1.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Upland cotton	Flood	9.7	9.7	9.7	3.4	0.5	0.0	0.0	0.0	0.0	0.0	0.0
Spring lettuce	Flood	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Fall lettuce	Flood	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Fall onions	Flood	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Mid season onions	Flood	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Spring onions	Flood	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Grain sorghum	Flood	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.1	0.0
Wheat	Flood	1.2	1.2	1.2	1.2	1.2	1.2	1.2	0.2	0.0	0.0	0.0
Green chile	Flood	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Red chile	Flood	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Pecans	Flood	66.8	66.8	66.8	66.8	66.8	66.8	66.8	66.8	66.8	66.8	60.0
Alfalfa	Drip	0.0	0.0	0.0	0.0	46.8	57.6	72.0	72.0	72.0	72.0	72.0
Pima cotton	Drip	0.0	0.0	0.0	3.1	4.7	6.0	7.5	9.0	9.0	9.0	9.0
Upland cotton	Drip	0.0	0.0	0.0	7.9	11.5	12.1	12.1	12.1	12.1	12.1	12.1
Spring lettuce	Drip	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Fall lettuce	Drip	7.6	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
Fall onions	Drip	8.9	8.9	8.9	8.9	8.9	8.9	8.9	8.9	8.9	8.9	8.9
Mid season onions	Drip	8.1	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2	10.2
Spring onions	Drip	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1	12.1
Grain sorghum	Drip	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.4
Wheat	Drip	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.2	1.4	1.4	1.4
Green chile	Drip	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6	6.6
Red chile	Drip	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2	7.2
Pecans	Drip	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.6
Total consumption	Flood	139.9	139.5	139.5	130.7	89.0	79.9	68.3	67.4	67.2	66.9	60.0
Total consumption	Drip	50.8	53.4	53.4	64.4	116.5	129.2	145.1	147.7	148.0	148.3	157.0
Grand total	Total	190.7	192.9	192.9	195.1	205.5	209.1	213.4	215.1	215.2	215.3	217.0
Change in water consumption (ref, no subsidy)	Total	0.0	2.2	2.2	4.4	14.8	18.4	22.7	24.4	24.5	24.5	26.3

are fairly self-explanatory, and are entirely compatible with the earlier tables. However, increased reservoir evaporation associated with the subsidy may be less obvious and requires explanation: more water is consumed by EBID crop irrigation under the increased subsidy levels because the higher crop yields require more ET. One source of additional water is slightly higher reservoir levels, as already described in Table 7. Higher reservoir storage volume in the hot dry climate of the Basin given the shape of its reservoirs means that these reservoirs will expose greater surface area to support the greater storage volumes. Higher surface area means higher evaporation. So our results show that the greater crop water use required to support higher yields under drip irrigation will require approximately 23,000 additional acre feet of crop water ET, but will also incur an additional 52,000 af of reservoir evaporation needed to support the extra reservoir deliveries to EBID crop water consumption.[18]

4. Conclusions and discussion

This paper analyzed the economics of a water conservation subsidy for irrigated agriculture. It examined a public program that would subsidize the capital cost of drip irrigation. It applied the subsidy to irrigated agriculture in New Mexico's part of the Rio Grande Project, USA.

Our results show that increased public subsidy of drip irrigation produces increased gross revenue from crop production, increased farm income, increased crop production, increased land irrigated under drip irrigation, and increased total irrigated land in production. Remarkably, our findings also show that water conservation subsidies reduce water applied to crops, but increase crop water consumption (ET), both at the per acre level and at the level of the total entire area farmed. Drip irrigation increases crop yields by raising crop water consumption, so the Basin's total water consumed by irrigated agriculture increases with higher subsidies of drip irrigation. Our findings lead us to conclude that where alternative irrigation technologies increase crop yields through more precise timing and quantities of irrigation to match a crop's needs, programs subsidizing these technologies are likely to increase crop water consumption. Without special administrative action guarding against this outcome, such policy actions may reduce water supplies available for groundwater pumpers, downstream uses, environmental uses, and uses by future generations. Our findings suggest reexamining the belief widely held by donors that programs providing incentives for promoting water-conserving technologies will relieve the world's water crisis.[19] Our results from the Rio Grande show that where aquifer recharge is an important source of water supply, adoption of drip irrigation measures can redistribute the Basin's water supply, reducing water available for uses outside agriculture in favor of increased water consumption by irrigated agriculture. Such impacts could impair existing water right holders who depend on surface return flows or aquifer recharge. Drip irrigation is important for many reasons, including higher farm income, higher crop yields, and improved food security. However, it does not necessarily save water when considered from the scale of a river basin's hydrologic balance.

An important question revolves around whether or not the increase in net farm income offsets the reduced benefits of lower surface return

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[18] Higher reservoir levels also produce additional recreation benefits. Recreation benefits increase from $22.0 million per year in the Basin with no drip irrigation subsidy to $23.5 million per year under the maximum subsidy. So additional crop irrigation water requirements complement additional reservoir recreation benefits in both the hydrologic and economic sense.

[19] In recent years crop yields have increased dramatically in the upper part of the Basin in southern Colorado. Crop yields here have increased considerably since the mid 1980s. Those increased yields coupled with changing irrigation practices have worked to increase overall water depletions. Similar problems of falling aquifers have been reported in parts of the Snake River Basin in Idaho where flood irrigation has been replaced by technologies that apply less water but consume more.

Table 5
Farm income by crop, technology, and conservation subsidy, lower Rio Grande, NM, USA, annual average, 1000 US dollars per year, 2006–2025.

Crop	Irrigation technology	Water conservation subsidy as a percentage of capital cost										
		0	10	20	30	40	50	60	70	80	90	100
Alfalfa	Flood	10,464	10,464	10,464	10,464	3663	2093	0	0	0	0	0
Pima cotton	Flood	62	62	62	22	0	0	0	0	0	0	0
Upland cotton	Flood	0	0	0	0	0	0	0	0	0	0	0
Spring lettuce	Flood	0	0	0	0	0	0	0	0	0	0	0
Fall lettuce	Flood	61	0	0	0	0	0	0	0	0	0	0
Fall onions	Flood	0	0	0	0	0	0	0	0	0	0	0
Mid season onions	Flood	0	0	0	0	0	0	0	0	0	0	0
Spring onions	Flood	0	0	0	0	0	0	0	0	0	0	0
Grain sorghum	Flood	0	0	0	0	0	0	0	0	0	0	0
Wheat	Flood	0	0	0	0	0	0	0	0	0	0	0
Green chile	Flood	0	0	0	0	0	0	0	0	0	0	0
Red chile	Flood	0	0	0	0	0	0	0	0	0	0	0
Pecans	Flood	24,133	24,133	24,133	24,133	24,133	24,133	24,133	24,133	24,133	24,133	21,649
Alfalfa	Drip	0	0	0	0	5165	7138	9899	10,875	11,851	12,827	13,803
Pima cotton	Drip	0	0	0	0	23	178	407	709	930	1152	1373
Upland cotton	Drip	0	0	0	0	0	0	0	105	404	704	1003
Spring lettuce	Drip	0	0	0	0	0	0	0	0	0	0	0
Fall lettuce	Drip	1065	1284	1446	1609	1772	1934	2097	2260	2422	2585	2748
Fall onions	Drip	6676	6806	6936	7067	7197	7327	7457	7587	7717	7847	7978
Mid season onions	Drip	457	704	834	964	1094	1224	1355	1485	1615	1745	1875
Spring onions	Drip	1257	1387	1517	1648	1778	1908	2038	2168	2298	2428	2559
Grain sorghum	Drip	0	0	0	0	0	0	0	0	0	0	0
Wheat	Drip	0	0	0	0	0	0	0	0	0	0	0
Green chile	Drip	2237	2335	2433	2530	2628	2725	2823	2921	3018	3116	3213
Red chile	Drip	1408	1506	1603	1701	1799	1896	1994	2091	2189	2287	2384
Pecans	Drip	0	0	0	0	0	0	0	0	0	0	2135
Total income	Flood	33,848	33,842	33,842	34,222	27,593	26,056	23,963	24,046	24,066	24,116	21,649
Total income	Drip	12,989	13,862	14,621	14,609	20,575	23,722	27,770	30,000	32,268	34,509	38,935
Grand total farm income	Total	46,837	47,704	48,463	48,832	48,168	49,777	51,733	54,045	56,334	58,625	60,584
Change in farm income (ref no subsidy)	Total	0	867	1626	1995	1331	2941	4896	7208	9498	11,788	13,747

flows, reduced seepage, and falling aquifer levels. Our results from the Rio Grande show that with sufficiently high taxpayer subsidies of drip irrigation, the gain in the Basin's farm income is higher than the loss of other economic values of water. So from the Basin's view, overall economic benefits from all major uses of water still increase despite the increased water consumption by irrigated agriculture.

4.1. Integration

Water management at the basin scale presents major challenges because of diverse interactions among the biophysical system, economic values, and institutions. This paper has described and illustrated a way to integrate biophysical, institutional and economic elements of a river basin into a unified framework to guide policy. Our approach rests on several elements:

- Hydrology: we balance surface and groundwater stocks and flows spatially and temporally.
- Institutions: we identify institutional constraints that govern the use, development, storage, and movement of water among locations, uses, and time periods.
- Economics: we measure the economic benefits of water uses and environments in various times and places.
- Replicating status quo: we calculate water use patterns and economic benefits that are determined by existing policies and are governed by existing institutions.

Table 6
Economic benefits by location and farm water conservation subsidy level, Rio Grande Basin, USA, annual average, 1000 US dollars per year, 2006–2025.

Location in Basin	State	Use	Farm water conservation subsidy (percentage of capital cost)										
			0	10	20	30	40	50	60	70	80	90	100
From water use													
Rio Grande Conservancy District	CO	Ag	33,051	33,051	33,051	33,051	33,051	33,051	33,051	33,053	33,053	33,053	33,053
Albuquerque	NM	Urban	282,744	282,745	282,745	282,745	282,745	282,744	282,745	282,736	282,736	282,746	282,747
Middle Rio Grande Conservancy District	Nm	Ag	2472	2472	2472	2472	2472	2472	2472	2472	2472	2472	2472
Elephant Butte Irrigation District	NM	Ag	46,837	47,704	48,463	48,832	48,168	49,777	51,733	54,045	56,334	58,625	60,584
El Paso	TX	Urban	276,049	276,054	276,054	276,057	276,068	276,068	276,068	275,873	275,873	276,071	276,073
El Paso County Water Improvement District	TX	Ag	5851	5851	5851	5851	5851	5851	5851	5841	5841	5851	5851
From water environment													
Heron Reservoir	NM	Recreation	5919	5919	5919	5977	6022	6046	6050	6065	6065	6205	6205
El Vado Reservoir	NM	Recreation	5168	5168	5168	5181	5196	5192	5197	5206	5206	5236	5236
Abiquiu Reservoir	NM	Recreation	7034	7035	7035	7147	7228	7376	7421	7471	7472	8144	8154
Cochiti Reservoir	NM	Recreation	1471	1471	1471	1468	1468	1468	1468	1469	1469	1473	1472
Elephant Butte Reservoir	NM	Recreation	1996	1996	1996	2016	2040	2055	2060	2079	2079	2082	2084
Caballo Reservoir	NM	Recreation	430	430	430	431	421	411	411	411	411	403	391
Total benefits, water use			647,004	647,876	648,635	649,007	648,355	649,964	651,919	654,020	656,309	658,818	660,780
Total benefits, water environment			22,017	22,019	22,019	22,219	22,375	22,548	22,608	22,701	22,702	23,542	23,542
Basin-wide total economic benefits			669,021	669,896	670,655	671,226	670,729	672,512	674,527	676,721	679,011	682,360	684,322

Table 7
Reservoir storage levels by water conservation subsidy level, Rio Grande Basin, USA, annual average, 1000 af, 2006–2025.

Reservoir name	Farm water conservation subsidy (percentage of capital cost)										
	0	10	20	30	40	50	60	70	80	90	100
Heron Reservoir, NM	268	268	268	278	285	290	290	293	293	316	316
El Vado Reservoir, NM	138	138	138	140	142	142	142	144	144	148	148
Abiquiu Reservoir, NM	603	604	604	630	644	685	706	703	704	901	902
Cochiti Reservoir, NM	643	643	643	639	645	641	643	646	646	663	667
Elephant Butte Reservoir, NM	1473	1474	1474	1489	1522	1540	1552	1587	1587	1692	1701
Caballo Reservoir, NM	35	35	35	35	28	22	21	21	21	15	7
Total reservoir storage	3160	3161	3161	3211	3266	3319	3356	3394	3395	3736	3742

- Improving status quo: we describe a path for increasing the total economic value of water by examining how existing water use patterns and economic benefits can be altered by a new policy while still being governed by existing institutions.

4.2. Adaptation

This paper has presented a decision support tool for linking various aspects of water management that occur in a river basin. The application was to irrigation water conservation subsidies in the Rio Grande Basin. But how does it adapt to other basins, climates, cultures, institutions, economic values, and economic systems? Our framework was designed to be adaptable.

River basin frameworks are hungry for data. Applying the model to a different basin requires a schematic that spatially summarizes sources and uses of water. A schematic like the one in Fig. 1 is needed to build the model so it tracks water use patterns accurately from the watershed's top to bottom. After getting the basin's plumbing right, our approach also needs data on headwater flows, reservoir storage capacities, reservoir storage levels, irrigated land capacity, irrigated acreage in production, crop mix, and farm production costs, yields, and prices. It needs data on costs of urban water supply, delivery capacity, prices charged, price elasticities of demand, and number of customers. It also requires information on institutions. These are the rules that require or limit water use patterns, regulate groundwater pumping, mandate water deliveries from various upstream to downstream locations, as well as environmental, engineering, or legal constraints that set minimum or maximum streamflows. Taken together, these data provide the information required by the model to optimize water use patterns for any basin based on its supply, agronomic conditions, and economic values of water, while being consistent with its institutions. The decision support tool can optimize water use patterns for the current period. Where forecast data are available, the optimization tool can be applied to future periods. Our approach can be a useful tool to support evaluations for current (ex-post) policy arrangements or for planned (ex-ante) policy proposals.

For all these reasons, we are optimistic about the transferability of our approach from the Rio Grande Basin. Our research group has developed similar basin scale decision support tools for the Nilüfer Basin in Turkey (Gürlük and Ward, 2009) and the Nile Basin in Egypt (Abdallah, 2008). Furthermore, our group and its partners are in the early stages of developing a decision support tool for improved farm income and food security for the Balkh River Basin in Afghanistan. Water storage expansion proposals are receiving special scrutiny in that basin. Culture, institutions, hydrology, land tenure, crop mix, food security issues, and values of water are different there than in the Rio Grande. Yet, despite those differences, building a decision support tool to inform policy debates is arguably more important for the Balkh Basin than for the Rio Grande. In Afghanistan, the cost of failure to find policies that optimize water use exacts a higher toll in human suffering. Decision support tools are here to stay. Worldwide, we will continue to be asked to find ways to get more value from available water supplies that see growing scarcity in the face of climate change, population growth, and food security challenges.

Table 8
Surface water use by farm water conservation subsidy level, Rio Grande Basin, USA, annual average, 1000 af/year, 2006–2025.

Location in basin	Use	Farm water conservation subsidy (percentage of capital cost)										
		0	10	20	30	40	50	60	70	80	90	100
Water consumption[a]												
Rio Grande Conservancy District	Agriculture	353	353	353	353	353	353	353	353	353	353	353
Albuquerque	Urban	59	59	59	59	59	59	59	59	59	59	59
Middle Rio Grande Conservancy District	Agriculture	66	66	66	66	66	66	66	66	66	66	66
Elephant Butte Irrigation District	Agriculture	191	193	193	195	206	209	213	215	215	215	217
Ciudad Juarez, Mexico area	Agriculture	26	26	26	26	26	26	26	31	31	26	26
El Paso	Urban	71	71	71	71	71	71	71	71	71	71	71
El Paso County Water Improvement District	Agriculture	56	56	56	56	56	56	56	56	56	56	56
Evaporation												
Heron Reservoir, New Mexico	Reservoir	18.4	18.4	18.4	19.1	19.6	19.9	20.0	20.2	20.2	21.8	21.8
El Vado Reservoir, New Mexico	Reservoir	11.1	11.1	11.1	11.2	11.4	11.4	11.4	11.5	11.5	11.9	11.9
Abiquiu Reservoir, New Mexico	Reservoir	28.5	28.5	28.5	29.7	30.4	32.3	33.4	33.2	33.2	42.6	42.6
Cochiti Reservoir, New Mexico	Reservoir	73.7	73.8	73.8	73.3	74.0	73.5	73.8	74.1	74.1	76.1	76.5
Elephant Butte Reservoir, New Mexico	Reservoir	238.0	238.0	238.0	240.5	245.8	248.8	250.6	256.3	256.3	273.3	274.8
Caballo Reservoir, New Mexico	Reservoir	11.2	11.2	11.2	11.4	9.1	7.0	6.9	6.9	6.9	4.9	2.3
Total consumption from beneficial use		823	825	825	827	837	841	845	852	852	847	849
Total reservoir evaporation		381	381	381	385	390	393	396	402	402	430	430
Total use from consumption and evaporation		1203	1206	1206	1212	1228	1234	1241	1255	1255	1277	1278
Total change in use (ref 0% subsidy)		0	2	2	9	24	30	38	51	51	74	75

[a] Water consumption refers to consumptive use for urban areas and to crop water ET for irrigated area.

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