ECONOMIC COSTS AND BENEFITS OF INSTREAM FLOW PROTECTION FOR ENDANGERED SPECIES IN AN INTERNATIONAL BASIN[1]

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ABSTRACT: The U.S. Endangered Species Act (ESA) restricts federal agencies from carrying out actions that jeopardize the continued existence of any endangered species. The U.S. Supreme Court has emphasized that the language of the ESA and its amendments permits few exceptions to the requirement to give endangered species the highest priority. This paper estimates economic costs associated with one measure for increasing instream flows to meet critical habitat requirements of the endangered Rio Grande silvery minnow. Impacts are derived from an integrated regional model of the hydrology, economics, and institutions of the upper Rio Grande Basin in Colorado, New Mexico, Texas, and Mexico. One proposal for providing minimum streamflows to protect the silvery minnow from extinction would provide guaranteed year round streamflows of at least 50 cubic feet per second in the San Acacia reach of the upper Rio Grande. These added flows can be accomplished through reduced surface diversions by New Mexico water users in dry years when flows would otherwise be reduced below the critical level required by the minnow. Based on a 44-year simulation of future inflows to the basin, we find that some agricultural users suffer damages, but New Mexico water users as a whole do not incur damages from a policy that reduces stream depletions sufficiently to provide habitat for the minnow. The same policy actually benefits downstream users, producing average annual benefits of over $200,000 per year for west Texas agriculture, and over $1 million for El Paso municipal and industrial water users, respectively. Economic impacts of instream flow deliveries for the minnow are highest in drought years.
(KEY TERMS: water policy; instream flow; endangered species; irrigation; modeling; water law.)

BACKGROUND

The Rio Grande originates in the southern Colorado Rocky Mountains. It begins at the Continental Divide in Colorado's Weminuche Wilderness, which includes three 14,000 foot peaks: Mt. Eolus, 14,083 feet; Mt. Windom, 14,082 feet; and Sunlight Peak, 14,059 feet. The river flows through New Mexico, and forms the border between Texas and Mexico on its way to the Gulf of Mexico. Even under normal flow conditions, basin demands exceed supplies; emerging demands for environmental protection in the form of instream flows further increase competition for already scarce water. Overlaid on this is continued population growth, declining ground water levels, and deteriorating water quality.

The upper Rio Grande, which flows from its headwaters to about 70 miles south of the border cities of El Paso, Texas, USA, and Ciudad Juarez, Mexico, meets the primary water needs of three major cities and one million acres of irrigated land in the U.S. and Mexico. The lower Rio Grande begins downstream of Fort Quitman, Texas, with contributing inflows from Mexico, and continues to its mouth at the Gulf of Mexico. In 1906, the U.S.-Mexico water treaty (The Treaty) provided that 60,000 acre feet per year be delivered to Mexico. In 1938, the Rio Grande Compact (the Compact) was approved by Congress, dividing the annual water flow among Colorado, New Mexico, and Texas. In drafting the Compact, the three states considered both historical streamflow and historical water use patterns as well as the capabilities and limits of storage facilities when designing the three-state operating agreement for the river (Hill, 1974).

The Compact has proven to be a flexible institution for avoiding much legal conflict among the three states over scarce and random water supplies. Still, conditions at the time the Compact was negotiated could not have predicted the growth in the basin's

demand for water associated with a five-fold increase in regional population (Peach and Williams, 2000) or increased demands for streamflows to meet the needs of endangered species. While municipal and industrial (M&I) water demands in the major basin cities (Albuquerque, El Paso, and Ciudad Juarez) have historically been met by ground water, this pumping is not sustainable at current withdrawal rates. El Paso is rapidly increasing its use of surface water; Albuquerque plans to begin withdrawing surface water; and the largest basin municipality, Ciudad Juarez, is projected to deplete its current sole source of water in as little as a decade (Paso del Norte Water Task Force, 2001).

In 1973, Congress enacted the Endangered Species Act (ESA) to protect endangered and threatened species and the ecosystems on which they depend (Parker, 2002a). The ESA prohibits federal agencies from actions that jeopardize the continued existence of any endangered species. The U.S. Supreme Court has made it clear that this language of the ESA permits few exceptions to the requirement to assign top priority to endangered species. The ESA requires federal agencies to give first priority to the stated national policy of saving endangered species and to halt and reverse the trend toward species extinction at virtually any cost. The ESA, as amended several times through the late 1970s and 1980s, allows various exemptions and economic considerations. For example, the designation of Final Critical Habitat, as ongoing with the silvery minnow, requires the consideration of economic consequences of that designation, and allows for exemptions (e.g., for partial acreage) due to severe economic impacts. The amendments also created the provisions for a final God Squad exemption process. Partial exemptions or changes made under the economic analysis component of the ESA have happened frequently; complete exemptions under the God Squad provisions remain a rare event.

Despite the judicial and legislative requirement that species be saved at virtually any cost, it is important to establish information on the economic cost of ensuring species' survival so that various proposals for saving the species can be compared. Lower cost measures for protecting species are economically preferred to higher cost ones. Because of the high cost of guaranteeing survival of some water dependent species in places where water is scarce and subject to many competing demands, it is especially important to search for lower cost methods for saving species consistent with the biological requirements of the species.

The Rio Grande silvery minnow (*Hybognathus amarus*), hereafter referred to as the minnow, was officially listed as an endangered species by the U.S.

Fish and Wildlife Service in 1994. As of 2002, the 176-mile stretch of the Rio Grande Basin between Cochiti Dam and the Elephant Butte Reservoir headwaters where the minnow is found is about 5 percent of the minnow's historic range. Diversion dams in this area restrict the upstream movement of the minnow. Its only remaining habitat has been degraded significantly, making the habitat progressively less desirable to the minnow. The minnow lays eggs that float downstream. Historically, the minnow repopulated upstream areas by the young and adult fish swimming upstream in low flow periods. Dams and diversion structures have contributed to restricting natural upstream repopulation, resulting in greater concentration of the remaining minnows in the San Acacia reach (Parker, 2002b).

Several studies have been completed since the mid 1990s that examine economic consequences of allocating scarce water to protect endangered species, instream flows, and other environmental needs. Gillig *et al.* (2001) examined economic/environmental tradeoffs through development of an integrated hydrological, economic, and environmental model of the Edwards Aquifer in Texas. Green and O'Connor (2001) examined water banking as a method to secure endangered species habitat in the Snake River. Huppert (1999) examined economic costs of recovering the endangered Snake River salmon. Keplinger *et al.* (1998) examined payments required to reduce agricultural diversions from the Edwards Aquifer in Texas to promote environmental needs. Moore *et al.* (1996) analyzed tradeoffs between endangered fish species and irrigated agriculture for the 17 western states. Naeser and Smith (1995) examined measures for securing instream flows to improve the aquatic environment in the Arkansas River, Colorado. Paulsen and Wernstedt (1995) analyzed the cost effectiveness of various salmon recovery methods in the Columbia Basin. Raffiee *et al.* (1997) estimated economic costs of more than $160 million to increase by two percent the survival probability of an endangered Nevada fish. Turner and Perry (1997) examined least cost strategies for increasing instream flows for environmental benefits in Oregon's Deschutes River basin. Willis *et al.* (1998) looked for ways to minimize economic damages to irrigated agriculture associated with setting up a contingent water contract to protect three species of endangered salmon during critical low flow periods.

This paper examines economic costs of meeting habitat needs for the silvery minnow. It focuses on the (1) level, (2) distribution, and (3) economic benefit associated with agricultural and municipal uses of water as well as how all three would change in the face of delivering streamflows needed to protect the minnow from extinction.

According to a biological opinion issued by the U.S. Fish and Wildlife Service on June 29, 2001, the minnow requires continuous minimum streamflows of at least 50 cubic feet per second (cfs) over the San Acacia Diversion Dam in the San Acacia reach of the Rio Grande mainstem (U.S. Department of Interior, 2001). A reach is that part of a river extending downstream from a given point for which the reach is named to the river's next significant physical feature. The San Acacia reach runs from the San Acacia diversion dam to Elephant Butte Reservoir (Figure 1). It is about 60 miles long, represents a small part of the minnow's historic range, is currently the most productive reach for numbers of minnows, and is that section of the river most prone to drying (Parker, 2002a). This June 2001 biological opinion established 50 cfs minimum flow requirement at the San Acacia reach from July 1 to October 31.

This area is part of the Rio Grande mainstem where the minnow still survives in a 176 mile stretch between Cochiti Reservoir and Elephant Butte Reservoir (Figure 1). Historically, many stretches of the river in this region have seen zero flow in summer months, and these low flows typically have been most pronounced in drought periods.

This paper's objective is to identify economic impacts to both agricultural and municipal and industrial (M&I) water users associated with measures that would assure year round minimum flows in this reach equal to at least 50 cfs. We refer to these flows as minnow flows. In estimating these impacts, rules defined by the existing Compact and Treaty obligations are enforced while also meeting minnow flow requirements. Policy options are examined by use of a recently developed integrated model of the basin. The model includes important elements of the basin hydrology, institutions, and economics to estimate basin wide benefits of alternative policies. The Appendix describes the most important equations used for the model. Additional details, and the model code, are described elsewhere (Ward *et al.,* 2001).

OPPORTUNITIES AND BARRIERS FOR INSTREAM FLOW PROTECTION

The presence of Elephant Butte Reservoir downstream of the river reach occupied by the minnow allows for significant operational flexibility in the timing of flows as they pass the San Acacia reach before they enter Elephant Butte Reservoir. Historical operation of the Rio Grande in the San Acacia reach has resulted in various reaches of the Rio Grande mainstem going dry for extended periods without compromising Compact or Treaty obligations. This occurred,

for example, in 1996 when a dry year combined with irrigation withdrawals in the Middle Rio Grande Conservancy District (MRGCD) led to several dry periods in the San Acacia reach. MRGCD is an organization of farm producers that irrigates lands from Cochiti to Elephant Butte Reservoirs (Figure 1).

Based on historical flows since the early 20th Century, approximately three out of every ten years have produced even greater water scarcity in the San Acacia reach than was observed in 1996. Flows affecting minnow habitat in the San Acacia reach are thus dependent on intrastate, interstate, and international water institutions as well as on the management actions of private water users and federal water agencies.

The drought year of 2002 and minnow flow requirements strained the relationship between private and federal water managers and water users. For example, on Wednesday, October 16, a federal appeals court suspended Judge James Parker's September 23 order to release water into the low flowing Rio Grande to save the minnow. The Tenth U.S. Circuit Court of Appeals granted requests by the State of New Mexico, the City of Albuquerque, and the MRGCD to delay Judge Parker's order, which authorized streamflows in the Rio Grande to continue at the rate of 50 cfs through the San Acacia reach. Parker suggested the water come from Heron Reservoir in the Rio Chama Basin in northern New Mexico, which stores water for cities, farmers, and other contractors. The appeals panel said the judge's order should be delayed while the defendants pursue an appeal. The court said the appeals raised legitimate questions over the contracts governing the use of Heron Reservoir in New Mexico. On October 18, U.S. Supreme Court Justice Stephen Breyer refused to block the appeals court ruling. The drama continues.

METHODS OF ANALYSIS

As part of a recent study on severe and sustained drought in the Rio Grande Basin (Ward *et al.,* 2001), an integrated model of the Rio Grande Basin was developed to bring the region's hydrology, economics, and institutions within a single framework for policy analysis. The integrated framework allows analysis of alternative water management institutions. At the same time, the framework accounts for physical interactions between uses (agricultural, municipal, instream, and environmental), storage (including ground water), flows (including diversions, pumping from ground water, and return flows), and various losses (including field, canal, and conveyance).
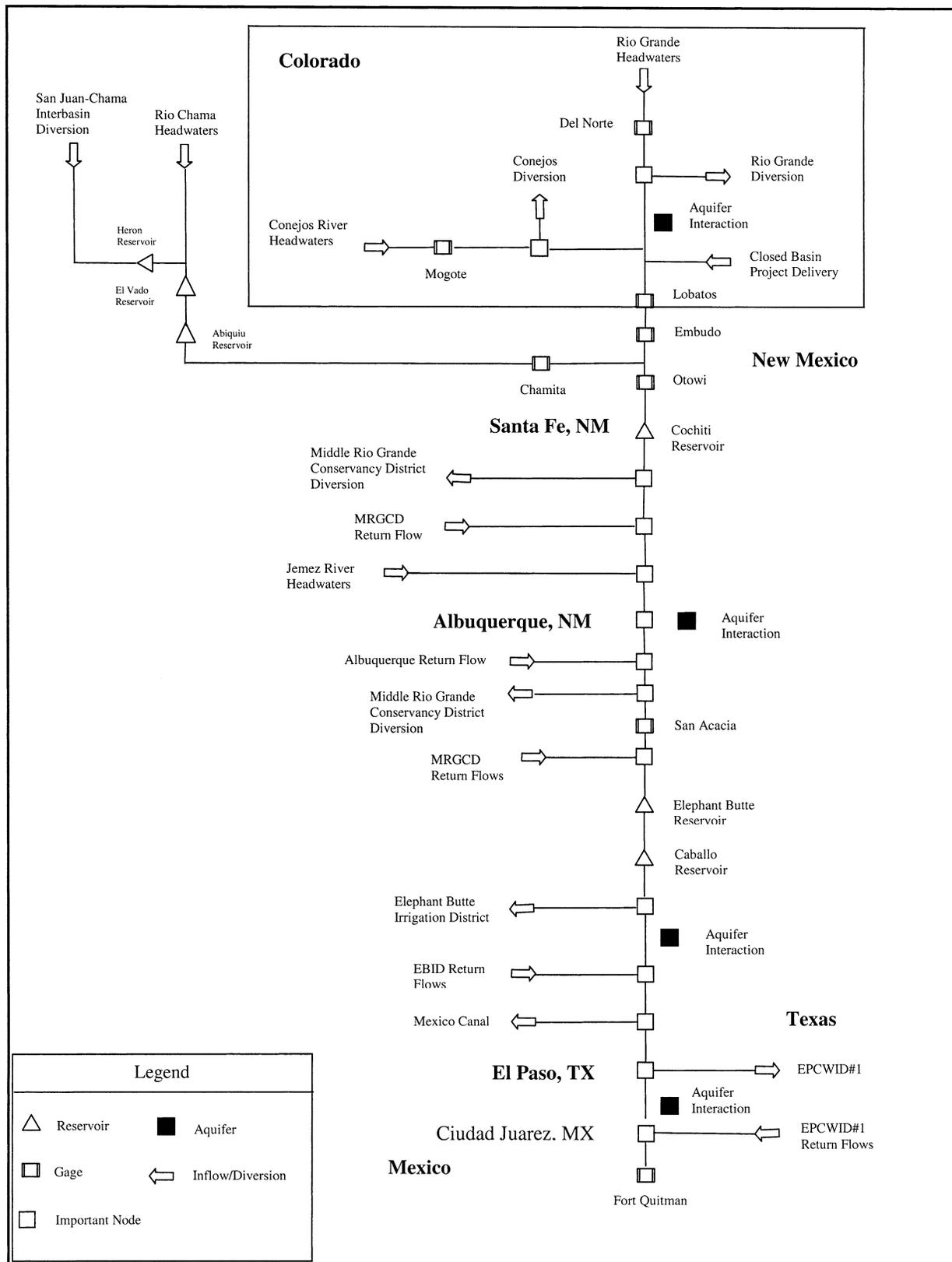
Figure 1. Schematic of Rio Grande Basin.

Because of the importance of interstate and international water policy issues, relevant compacts, uses, storage, and flows are all represented.

The model starts with the basic water supply, which includes all major tributaries, interbasin transfers, and hydrologically connected ground water. Water demands, current and projected up to 44 years, include agricultural water uses, M&I demands in Albuquerque and El Paso, recreation at the major basin reservoirs, and environmental demands for minnow flows. Each component is represented in a yearly time step over the 44-year planning horizon.

Water Allocation Under the Rio Grande Compact

The Rio Grande Compact establishes schedules relating each state's obligation to the next state downstream on the basis of the upstream state's available water supply. The Treaty obliges the United States to deliver annually 60,000 acre feet to Mexico, except in periods of extraordinary drought.

Allocations under the Compact (New Mexico Water Resources Research Institute, 1997) and Treaty were represented using the model. Central to the Compact is a set of supply indices specifying the proportion of inflows to one state delivered to the downstream state.

Beginning at the top of the basin, according to Articles III and IV of the Compact, Colorado must deliver to New Mexico in any given year a minimum water volume based on that year's headwater runoff. According to the Compact, Colorado may use from 40 to 80 percent of its total runoff (Equation A7).

Next, under Article V of the Compact, New Mexico must deliver annual flows to Texas, defined as all lands downstream of Elephant Butte Reservoir (Equation A8). For New Mexico lands that lie above Elephant Butte Reservoir in the Rio Grande Basin, annual consumptive use is constrained by supply and export demand. Supply consists of (1) Colorado's deliveries to New Mexico, (2) runoff produced inside New Mexico, and (3) interbasin transfers into New Mexico. According to the Compact, any interbasin transfers into the Rio Grande Basin can be fully used in New Mexico above Elephant Butte and are exempt from New Mexico's delivery requirements to Texas. Export demand consists of delivery requirements to Texas and Mexico.

U.S. deliveries to Mexico under the Treaty obligations are made by releases from Elephant Butte Reservoir. After Mexico's 60,000 acre feet are supplied, under the historical operation of the Rio Grande Project below Elephant Butte, New Mexico lands receive 57 percent of the annual flows, while Texas lands receive 43 percent.

Minimum Flows for Endangered Species

Hydrologic analysis of streamflows was conducted to estimate the amount by which annual water use in the basin would need to be adjusted to provide minnow flows at the San Acacia reach. Total water use in central New Mexico will fall as a consequence of providing minnow flows, while water use in southern New Mexico and Texas will increase. After the water passes the San Acacia reach, it ends up in Elephant Butte Reservoir and is available for beneficial use in southern New Mexico and Texas.

Because the model was originally designed for an annual time step, a method was developed to translate minimum average daily minnow flows to equivalent reductions in annual stream depletions that would be sufficient to produce those flows. The method examined how total annual historical streamflow deficits at critical stream reaches compared to total annual historical flow that passed that reach.

The San Acacia gauge was chosen to measure required minnow flows in the San Acacia reach. Using 1959 through 2001 data on average daily flows at the San Acacia gauge, a simple linear regression shows the relationship between annual total acre feet of deficit at the San Acacia gauge produced by total annual acre feet of flow at the gauge. Annual deficit is defined as total acre feet shortfall produced over all days of the year in which flows are less than 50 cfs. These annual flow deficits at the Rio Grande mainstem San Acacia gauge were computed for all years, 1959 through 2001.

The following regression equation tests the hypothesis that greater annual flow contributes to smaller annual streamflow deficits, assuming that other relevant factors excluded from the equation stay the same:

Deficit =

$$7770 + 2403*yr < 70 - 5257*yr > 99 - .00578*Flow \quad (1)$$
$$(990) \quad (967) \quad (2641) \quad (.00093)$$

where *Deficit* is the cumulative annual acre feet shortfall for years when flows were less than 50 cfs; $yr < 70$ is the 0 to 1 dummy variable taking on a value of 1 for all years before 1970; $yr > 99$ is the 0 to 1 dummy variable taking on a value of 1 for all years after 1999; and *Flow* is the total annual streamflow measured in acre feet at the San Acacia gauge.

Estimated standard errors are displayed below each coefficient. The overall F statistic is 22.20, which is an observed probability of nonzero regression relation less than .0001. The adjusted R^2 equals 0.61. The Durbin-Watson test for first order autocorrelation

equals 1.41, which is not critically low enough (d_L = 1.34) to require special adjustment for the time series nature of the data.

This equation shows that since 1999, deficits at the San Acacia gauge fell by 5,257 acre feet per year. One interpretation of the negative 5,257 coefficient is that water managers have adjusted to the needs dictated by minnow flow requirements by producing smaller deficits in those more recent years. Stated differently, in years before 1999, a given amount of annual flow produced 5,257 acre feet more in deficits. Fort (2000) describes the history of institutional barriers to protecting instream flows in New Mexico.

Results of estimating annual minnow flow deficits in Equation (1) show that each 1000 acre feet per year of increased annual flows at the San Acacia gauge reduce average minnow streamflow deficits by about 5 acre feet without special mitigating action. That is, in the absence of special management to accommodate the needs of the minnow, one extra acre foot of additional flow at the gauge annually will produce 0.005 less deficit. No regression results prove causality, but only test hypotheses by showing the sign, size, and significance of coefficients.

That is, New Mexico water users above Elephant Butte Reservoir who reduce net depletions above the San Acacia gauge by the amount of the annual deficit, equal to about 2,500 acre feet (7,770 minus 5,257) in the driest years, will produce enough average additional flow to assure at least 50 cfs year round minimum flows for the minnow (Equation A9). The relatively small intercept term in the regression analysis comes from the fact that from 1996 to the end of 2001, average daily flows fell below 50 cfs on fewer than 25 days, and never fell below 25 cfs. In the wettest years, New Mexico water users need not reduce depletions at all to provide minnow flows.

RESULTS

Findings are presented both for the case where no special provision is made for minnow flows as well as for the case when adequate minnow flows are provided. Results are shown both for water use patterns and for economic benefits produced by those water use patterns. The term 'use' means surface water diversions plus ground water applications. It does not refer to net river depletion. Sources of information for all tables are Ward *et al.* (2001).

Law of the River: Without Minimum Streamflows

Water Use Patterns. Table 1 shows long run average inflows to the system as well as annual model-forecasted water use patterns by major system users. Model forecast water use patterns do not match historical use patterns for the 1942 to 1985 period because of projected population growth.

Inflows to the system equal historical inflows for the period 1942 to 1985, a period in which inflows were about 15 percent below the long run period of record. Results are based on flows of the forecast period equal to the 1942 to 1985 inflows in absolute water supplies, but with economic activity in the region based on future expected population growth and with existing institutions in place for managing the water, *without* guaranteed minnow flows.

There are many possible ways to generate inflows to the basin. One method is to build a stochastic model, in which flows are generated randomly while maintaining historic patterns (e.g., using historic means and variances). Another method, the one used for this paper, is to build a deterministic model that reproduced historic inflows over the study period, with no random terms introduced. We decided in favor of using historic flows after a lengthy discussion with basin water managers, who suggested they would have greater confidence in model results based on historically remembered water supply patterns. Still, historical flows do not repeat themselves. So important future research should examine the sensitivity of this study's results to various stochastic model specifications.

Average gauged inflows to the basin for this period were 1.4 million acre feet per year at the six headwater gauges. Averaged over that time period, these historical flows were: 617,000 acre feet per year from the Rio Grande at the Del Norte gauge, 309,000 from the three Conejos Index gauges, 391,000 from the Chama watershed, 45,000 from the Jemez River basin, 32,238 from the Rio Puerco basin, and 40,515 from the Rio Salado basin. Ungauged runoff to the basin below the Lobatos gauge from the Sangre de Cristo mountain range in northern New Mexico produces a significant amount of water added to flows from the six headwater inflow gauges.

Over this forecast period where the system is operated under the current Law of the River, Colorado agriculture diverts about 788,000 acre feet per year of total water, of which about 616,000 comes from surface water and the remaining 172,000 from ground water pumping.

Rio Grande Basin water users are forecast to divert different amounts than they diverted in the actual 1942 to 1985 period because of anticipated growth in

TABLE 1. Water Use Patterns by State, Location, and User (1,000s acre feet).

Institution: Without Guaranteed Flows for Silvery Minnow.

Water Supply Scenario: 1942 to 1985 Historical Inflows (1.40 million acre feet per year) at Six Headwater Gauges

	Colorado	New Mexico				Texas	
	San Luis Valley Agriculture	Middle Rio Grande Agriculture Above Albuquerque	Albuquerque M&I	Middle Rio Grande Agriculture Below Albuquerque	Elephant Butte Agriculture	El Paso M&I	El Paso Agriculture
Average Annual Total Water Use	787.85	470.47	221.61	235.24	565.72	214.76	206.30
Average Annual Surface Water Use (diversion)	616.27	470.47	71.23	235.24	429.26	120.52	206.30
Average Annual Ground Water Use (pumping)	171.58	0.00	150.38	0.00	136.46	94.24	0.00
Average Total Water Use by State	787.85				1,493.04		421.06
Average Surface Water Use by State	616.27				1,206.20		326.82
Average Ground Water Use by State	171.58				286.84		94.24

Albuquerque M&I use and because Albuquerque plans to build surface treatment facilities that allow it to use its contracted San Juan Chama surface water. Averaged over the forecast period, future long run average annual water use under the water supply conditions described is: MRGCD agriculture above Albuquerque, 470,470 acre feet surface water per year diverted; Albuquerque area M&I use, 150,380 acre feet of ground water pumping and 71,230 acre feet of surface diversions; MRGCD agriculture below Albuquerque, 235,240 acre feet surface water diverted; Elephant Butte Irrigation District (EBID), 429,260 acre feet of surface water diverted and 136,460 acre feet of ground water.

For West Texas, long run average annual future water use is: El Paso M&I diverts 120,520 acre feet of surface water and 94,240 acre feet of ground water. El Paso agriculture diverts 206,300 acre feet of surface water.

Economic Benefits. Table 4 shows economic benefits produced by water use patterns without guaranteed minnow flows at the San Acacia reach. These are the benefits produced by water uses in the basin under the institution of the current Law of the River when total future inflow to the basin equals historical 1942 to 1985 supply.

Southern Colorado agriculture earns about $66 million average annual net income from its 145,000

acres in potatoes, alfalfa, and barley by diverting 787,850 acre feet of water, for an average of about $84 per acre foot diverted. The source for all hydrologic and economic results is Ward *et al.* (2001). Detailed model (GAMS) code is available from the authors. The model's essential equations are in the appendix.

In New Mexico, MRGCD agriculture earns about $6.4 million per year in the region above Albuquerque and about $2.0 million below Albuquerque from the 705,000 average annual acre feet of water diverted, or about $12 per acre foot diverted. Albuquerque M&I water use produces about $1.25 billion in total benefits from 221,600 acre feet of water use. Most of Albuquerque's high M&I benefit accrues to its rate payers as consumer surplus because of the low price of water compared to what people are willing to pay for M&I water, rather than go without.

This total benefit averages to slightly over $5,600 per acre foot diverted. South of Elephant Butte Reservoir, EBID crop and livestock producers earn about $28.4 million per year of net income from about 565,700 total acre feet diverted. Production consists chiefly of alfalfa, chile, pecans, onions, lettuce, and cotton, on about 82,600 acres of irrigated land, for which the water produces about $50 in net income per acre foot diverted.

In Texas, water use by El Paso M&I produces about $1.05 billion of total benefit, of which about 10 percent is as a direct water bill paid by M&I ratepayers.

Like Albuquerque, the high percentage of total water use benefit accrues as consumer surplus because the price elasticity of demand for water is low (between -0.10 and -0.20), and the average price charged (about $1.30/1000 gallons) is slightly below what ratepayers pay in other large southwestern cities and much lower than what El Paso ratepayers will pay as a maximum rather than go without. El Paso area agriculture earns about $16.7 million per year in farm income from 206,300 acre feet of water diverted from the river, which is about $80 per acre foot.

New Policy: With Minimum Streamflows

Water Use Patterns. Table 2 shows water use patterns in the basin that would occur with guaranteed minnow flows. Under the present system operation, these minnow flows could be delivered by a reduction of stream depletions of up to about 2,500 acre feet in dry years, as shown by Equation (1). These reduced stream depletions would occur if Albuquerque M&I users and MRGCD jointly reduced their use, compared to a policy without guaranteed minnow flows. Table 3 shows the change in water use brought about by requiring those minnow flows. Negative numbers indicate reduced water use and positive entries indicate increased water use.

Colorado water users are unaffected by the policy of meeting endangered species habitat in New Mexico because Colorado's delivery requirement under the Rio Grande Compact is not influenced by New Mexico's minnow flow requirements. Average annual water use falls in northern and central New Mexico by a total of just over 16,000 acre feet per year, which assures enough water for the minnow in the San Acacia reach. The difference between 16,000 acre feet of reduced diversions and approximately 2500 acre feet of reduced depletions is due to the high percentage of diversions that return to the stream above the San Acacia reach. Water use increases downstream of Elephant Butte Reservoir in southern New Mexico and west Texas as a consequence of New Mexico's minnow flows ending up in the reservoir.

Economic Benefits. Table 5 shows average annual economic benefits that would occur if minnow flows are provided, assuming, as before, projected future population growth in Albuquerque and El Paso. Table 6 shows changes produced by the policy of establishing minnow flows compared to results under conditions without the minnow flows. Studies by Berrens *et al.* (1996, 2000) use contingent valuation methods with a telephone survey to estimate significant unpriced economic values of protecting instream flows in New Mexico.

TABLE 2. Water Use Patterns by State, Location, and User (1,000s acre feet).

Institution: With Guaranteed Flows for Silvery Minnow.

Water Supply Scenario: 1942 to 1985 Historical Inflows (1.40 million acre feet per year) at Six Headwater Gauges

	Colorado	New Mexico				Texas	
	San Luis Valley Agriculture	**Middle Rio Grande Agriculture Above Albuquerque**	**Albuquerque M&I**	**Middle Rio Grande Agriculture Below Albuquerque**	**Elephant Butte Agriculture**	**El Paso M&I**	**El Paso Agriculture**
Average Annual Total Water Use	787.85	460.99	221.61	230.50	570.71	215.50	208.78
Average Annual Surface Water Use (diversion)	616.27	460.99	68.79	230.50	434.06	121.69	208.78
Average Annual Ground Water Use (pumping)	171.58	0.00	152.82	0.00	135.95	93.81	0.00
Average Total Water Use by State	787.85				1,483.11		424.28
Average Surface Water Use by State	616.27				1,194.34		330.47
Average Ground Water Use by State	171.58				288.77		93.81

TABLE 3. Change in Water Uses Produced by Guaranteed Flows for Silvery Minnow.

Water Supply Scenario: 1942 to 1985 Historical Inflows (1.40 million acre feet per year) at Six Headwater Gauges

	Colorado	New Mexico				Texas	
	San Luis Valley Agriculture	Middle Rio Grande Agriculture Above Albuquerque	Albuquerque M&I	Middle Rio Grande Agriculture Below Albuquerque	Elephant Butte Agriculture	El Paso M&I	El Paso Agriculture
Average Annual Total Water Use	0.00	-9.48	0.00	-4.74	4.29	0.74	2.48
Average Annual Surface Water Use (diversion)	0.00	-9.48	-2.44	-4.74	4.80	1.17	2.48
Average Annual Ground Water Use (pumping)	0.00	0.00	2.44	0.00	-0.51	-0.43	0.00
Average Total Water Use by State	0.00				-9.93		3.22
Average Surface Water Use by State	0.00				-11.86		3.65
Average Ground Water Use by State	0.00				1.93		-0.43

TABLE 4. Average Annual Economic Benefit From Water Use Patterns by State, Location, and User (1,000s acre feet).

Institution: Without Guaranteed Flows for Silvery Minnow.

Baseline Water Supply: 1942 to 1985 Historical Inflows (1.40 million acre feet per year) at Six Headwater Gauges

	Colorado	New Mexico				Texas	
	San Luis Valley Agriculture	Middle Rio Grande Agriculture Above Albuquerque	Albuquerque M&I	Middle Rio Grande Agriculture Below Albuquerque	Elephant Butte Agriculture	El Paso M&I	El Paso Agriculture
Average Annual Economic Benefit From Surface and Ground Water	66,390	6,423	1,246,441	1,992	28,366	1,054,719	16,714
Average Annual Economic Benefit Totaled by State	66,390				1,283,222		1,071,433

Colorado agriculture in the San Luis Valley suffers no economic losses from New Mexico's minnow flows for the same reason that it suffers no loss in water: Colorado's Rio Grande Compact delivery requirements do not depend on New Mexico's endangered species critical habitat needs.

In New Mexico, MRGCD agriculture incurs long run average losses of about $114,000 per year in reaches above Albuquerque and $35,000 per year in reaches below Albuquerque associated with reduced diversions into farmers' fields needed to provide minnow flows. These economic losses already began to occur in the year 2002, and could be higher in 2003, if minnow flows are enforced. High rainfall in the basin since late September 2002 kept the river channel wet without requiring reduced depletions by other water users.

Economic losses are higher in dry years but lower or even zero in wet years. Albuquerque M&I water use is virtually unchanged, but the city will substitute increased ground water pumping of about 2,400 acre feet for the same reduction in surface diversions needed for the minnow flows. The contribution of surface flows by Albuquerque to meet the minnow's needs will

TABLE 5. Average Annual Economic Benefit From Water Use Patterns by State, Location, and User (1,000s acre feet).

Institution: With Guaranteed Flows for Silvery Minnow.

Baseline Water Supply: 1942 to 1985 Historical Inflows (1.40 million acre feet per year) at Six Headwater Gauges

	Colorado	New Mexico				Texas	
	San Luis Valley Agriculture	Middle Rio Grande Agriculture Above Albuquerque	Albuquerque M&I	Middle Rio Grande Agriculture Below Albuquerque	Elephant Butte Agriculture	El Paso M&I	El Paso Agriculture
Average Annual Economic Benefit From Surface and Ground Water	66,390	6,309	1,246,417	1,957	28,583	1,055,994	16,917
Average Annual Economic Benefit Totaled by State	66,390				1,283,266		1,072,911

TABLE 6. Net Change in Average Annual Economic Benefit Produced by Guaranteed Flows for Silvery Minnows (1,000s acre feet).

Baseline Water Supply: 1942 to 1985 Historical Inflows (1.40 million acre feet per year) at Six Headwater Gauges

	Colorado	New Mexico				Texas	
	San Luis Valley Agriculture	Middle Rio Grande Agriculture Above Albuquerque	Albuquerque M&I	Middle Rio Grande Agriculture Below Albuquerque	Elephant Butte Agriculture	El Paso M&I	El Paso Agriculture
Net Change Due to Guaranteed Flows for Silvery Minnow	0	-114	-24	-35	217	1,275	203
Net Change Totaled by State	0				44		1,478

occur only after the city builds its surface treatment facilities. These facilities are expected to treat approximately 100,000 acre feet per year of its surface water. This increased reliance on more expensive ground water will increase costs to Albuquerque ratepayers by the rather modest amount of $24,000 compared to conditions without minnow flows. In southern New Mexico, EBID agriculture experiences an economic gain of about $217,000 per year on average, or $51 per additional acre foot. This gain occurs because of the larger amount of surface water that ends up in Elephant Butte Reservoir in those years when northern and central New Mexico provide minnow flows.

Under the Compact, New Mexico's contribution to minnow flows counts for increased credits or reduced debits to Texas. New Mexico must deliver to Texas a known quantity of water per year into Elephant Butte Reservoir based on the same year's total supply that flows past the Otowi stream gauge. Because the Compact requires a known total delivery to Texas, and because all minnow flows count for New Mexico's Compact deliveries, added deliveries required by the

minnow could be accomplished at a low total cost to New Mexico water users, in which cost is measured over an annual cycle. This cost is low because each added acre foot of minnow flows New Mexico contributes in dry periods is one acre foot less New Mexico owes to Texas in wet periods when streamflows are adequate. New Mexico's contribution to minnow flows redistributes Texas deliveries from one time period to another, but requires little net added flows over the year. If New Mexico meets its Compact delivery obligations to Texas both with and without minimum streamflows for the minnow, New Mexico water users might suffer virtually zero economic losses from the minnow flow deliveries. For this reason economic losses to New Mexico, as well as economic gains to Texas shown in Tables 5 and 6, are upper bounds.

In Texas, El Paso M&I users experience gains of about $1.3 million per year from slightly increased use over the long run, with ground water pumping falling slightly to make up for increased surface water supplies. Average benefits per added acre foot are about $1,700. El Paso area agriculture receives

$203,000 per year in direct farm income gains produced by greater surface flows delivered to Elephant Butte Reservoir. This gain is about one percent of benefits earned under a policy of no minnow flow requirements.

CONCLUSIONS

The U.S. Endangered Species Act and its amendments emphasize the protection of endangered species, with limited consideration of cost. Despite this emphasis, it is important to measure the economic costs of saving species so that people who are called upon to pay the money or water needed can contribute to informed choices for measures to save the species consistent with biological requirements.

This paper estimated the economic impacts associated with one measure for increasing instream flows to meet critical habitat requirements of the endangered Rio Grande silvery minnow. Using an integrated model of the hydrology, economics, and institutions of the Rio Grande Basin, a 44-year simulation of future inflows to the basin was conducted to estimate economic impacts of providing minimum acceptable flows for the minnow.

Protecting instream flows for the silvery minnow produces both economic gains and losses for agriculture and M&I uses of water for the upper Rio Grande Basin. Water uses affected by the minnow's protection are reallocated withing the basin. Water used for instream flow protection is run downstream to high valued agriculture and M&I uses (thanks go to an anonymous referee for this insight).

Economic benefits to New Mexico agriculture were estimated at $68,000 per year, distributed as a $149,000 loss to central New Mexico agriculture combined with a $217,000 gain to agriculture in southern New Mexico. These gains by southern New Mexico agriculture could compensate losses incurred by central New Mexico agriculture, with a residual net gain of $68,000. Annual average benefits lost to New Mexico M&I water users was a modest $24,000. So the net annual average gain to New Mexico associated with instream flow protection for the silvery minnow is $44,000. The policy of year round minnow flows produced a gain in benefit of $203,000 per year for El Paso Texas agriculture as well as a gain in benefit of $1,275,000 for El Paso M&I users.

APPENDIX
RIO GRANDE BASIN MODEL
MATHEMATICAL DOCUMENTATION

This appendix documents the essential elements of the Rio Grande Basin model described in the paper's text. Additional model details and the model's GAMS code (Brooke, *et al.,* 1992), are in Ward *et al.* (2001).

Inflow

Total inflows into the basin are defined as total annual flows at six headwater stream gauges. Inflow at each h-th headwater gauge in year t, X_{ht}, equals total source supplies

$$X_{ht} = Source_{ht} \qquad \text{(A1)}$$

Streamflow

Streamflow at the v-th river gauge in period t, X_{vt}, equals the sum of flows over each contributing source. Those sources are defined as total flows at all nodes X_{it} times a 0 to 1 matrix of elements M_{iv} indicating a contributing (1) or noncontributing (0) source. The M_{iv} matrix configures the basin. For each v-th river gauge, all immediately contributing upstream nodes take on a value of 1. Total flows, which cannot be negative, are

$$X_{vt} = \sum_i X_{it} M_{iv} \qquad \text{(A2)}$$

Use

Beneficial uses that require stream diversions are agriculture and M&I. Use at the s-th use node in t-th period, X_{st}, cannot exceed total supplies. Those supplies equal flows at each node X_{it}, multiplied by a 0 to 1 matrix of elements, W_{is}, indicating a contributing (1) or noncontributing (0) source. The W_{is} matrix configures the basin's use nodes. Total use, which cannot be negative, is

$$X_{st} = \sum_i X_{it} W_{is} \qquad \text{(A3)}$$

Return Flow

Each *s-th* use node is also an *r-th* return flow node for which a return flow coefficient, R_{rs}, is the proportion of the diversion returned to the stream in the same period as the diversion occurs. Flows returned to the stream at that node and period, X_{rt}, equal the sum over use nodes *s* of water uses times a diagonal matrix consisting of the return flow proportions R_{rs} on the main diagonal. The diagonal matrix structure permits assigning one element, *s*, to each return flow element, *r*, and avoids multiplying unlike set elements together. Total return flows are

$$X_{rt} = \sum_s X_{st} R_{rs} \tag{A4}$$

Groundwater Flow

Inflows into or outflows out of the river at the *w-th* ground water node in period *t*, defined as X_{wt}, occur from pumping outflows (less than 0) or seepage inflows (greater than 0). Parameters are set by the data matrix A_{wt}

$$X_{wt} = A_{wt} \tag{A5}$$

Reservoir Contents and Releases

An equation describes reservoir contents to track each reservoir's stocks of water in the *t-th* year. The *v-th* reservoir's contents in year *t*, Z_{vt}, equals its contents in the previous year, minus the net release (outflow minus inflow) from the reservoir, X_{Lt}, which contributes to added flow at the downstream node in that period. The diagonal matrix S_{Lv} keeps track of the *v-th* reservoir location in the basin, assures that its releases add to streamflow, and avoids multiplying unlike set elements. Reservoir contents are

$$Z_{vt} = Z_{vt-1} - \sum_L X_{Lt} S_{Lv} \tag{A6}$$

Contents of the *v-th* reservoir in the initial period (0) are defined by beginning watershed conditions, B_{ro}

$$Z_{v0} = B_{r0} \tag{A6a}$$

The reservoir's maximum contents are defined as:

$$Z_{v0}{}^{max} = C_v \tag{A6b}$$

This equation guarantees that the *v-th* reservoir's actual level can never exceed its capacity. Policies that would change a reservoir's capacity are simulated by altering the value of C_v.

Institutional Constraint: Rio Grande Compact.

The Compact, signed in 1938 by Colorado, New Mexico, and Texas, divides the annual flow of the Rio Grande. Under the Compact, each state receives more water in wetter years.

Articles III and IV of the Compact oblige Colorado to deliver water at the Colorado-New Mexico state line. These flows, measured at the Lobatos stream gauge (Figure 1), X_{tL}, must be at least

$$X_t{}^L \geq \theta_{0h} + X_{ht}\theta_{1h} + X_{ht}{}^2\theta_{2h} \tag{A7}$$

This quadratic equation approximates Colorado's total delivery requirements to New Mexico defined by Articles III and IV, and is based on annual source runoff measured at the headwater gauges, X_{ht}.

Article V of the Compact and the February 1948 resolution of the Compact oblige New Mexico to deliver water to Texas measured at the outflow of Elephant Butte Reservoir (Figure 1). New Mexico's delivery requirement to Texas is based on New Mexico's annual supply, defined as total flows at the Otowi stream gauge, north of Santa Fe, New Mexico. It is approximated in the model by:

$$X_t{}^E - X_{Lt}{}^E \geq \delta_{0h} + X_{vt}{}^o\delta_{1h} + \left(X_{vt}{}^o\right)^2\delta_{2h} \tag{A8}$$

where the *E* superscript indicates Elephant Butte Reservoir outflow, the location at which New Mexico must deliver water to Texas. The term $X_{vt}{}^O$ indicates annual flow at the Otowi gauge. The two left hand side terms are Elephant Butte Reservoir outflows ($X_t{}^E$) and net releases ($X_{Lt}{}^E$), respectively. The algebraic difference, $X_t{}^E - X_{Lt}{}^E$, plus reservoir evaporation is mathematically equivalent to the Elephant Butte Reservoir outflow plus the net change in reservoir storage, which is New Mexico's delivery requirement to Texas.

Institutional Constraint: Minimum Flows for Endangered Species

In 1994, the U.S. Fish and Wildlife Service listed the Rio Grande silvery minnow (*Hybognathus*

amarus) as an Endangered Species under the ESA. A biological opinion issued by the U.S. Fish and Wildlife Service (U.S. Department of the Interior, 2001) estimates that the minnow requires at least 50 cubic feet per second (cfs) of year round streamflow between the San Acacia gauge and the inflow to Elephant Butte Reservoir (Figure 1). A regression analysis showed that total annual deficits, defined as the total additional acre feet of water needed to overcome all shortages in streamflow below 50 cfs, takes the following form

$$X_{MT} \geq \varepsilon_{0v} + X_{vt}\, \varepsilon_{1v} \qquad (A9)$$

That is, minnow flow deficits past the San Acacia gauge (Figure 1), cannot exceed zero.

Annual streamflow shortfalls are equal to total acre feet of shortfalls based on 50 cfs continuous requirement for the silvery minnow. These shortfalls begin a maximum of ε_{0v} for a theoretic annual flow of zero, and are reduced by ε_{1v} for each added 1000 acre feet of annual added flow (Equation 1).

Economic Benefits

Economic benefit from all water used in the basin are defined in the model as total net income plus consumer surplus summed uses and time periods, equal to X_B. Diversions in the *t-th* period and *s-th* use, X_{st}, create economic benefits by being applied to the following quadratic total benefits function

$$X_B = \sum_s \sum_t X_{st} B_{1s} + \sum_s \sum_t X_{st}^2 B_{2s} \qquad (A10)$$

where B_{1s} and B_{2s} indicate parameters for the linear and quadratic terms, respectively, for the beneficial use at the *s-th* node. Reservoir/recreation benefits depend on reservoir stocks, and only depend on streamflows to the extent that streamflows affect reservoir levels.

For agricultural nodes, incremental benefits from added water use begin small (B_{1s} small but positive), then fall gradually with higher water use per acre as farm producers shift into water intensive, labor saving crops, such as cattle feed (B_{2s} is small but negative).

For M&I use nodes, incremental benefits from added use begin high as basic human requirements such as drinking and sanitation are met (B_{1s} is large and positive). Incremental M&I benefits fall rapidly as household water is applied to lower valued uses such as outdoor landscapes (B_{2s} is large and negative)

in the face of lower prices. Similarly, displaced incremental M&I benefits rise rapidly as droughts or other urban shortages become more severe and opportunities are reduced for painless conservation.

Total and marginal benefits for M&I water uses are based on estimated price elasticities of demand for El Paso and Albuquerque. Total benefits for agricultural uses are based on linear programming income maximization models. Data for these models come from published farm cost and return budgets for Colorado, New Mexico, and Texas. The income maximization models allow producers to shift from water using, labor saving activities into water saving, labor using activities as water scarcity increases. Increased water scarcity reduces water use, and increases the marginal value of remaining water as producers move back along their water demand functions, substituting land, labor, and capital for water.

Objective

Water use in the upper Rio Grande Basin model is heavily constrained by scarce water supplies and by existing institutions. We characterize these institutions as the "Law of the River," of which the Compact and Treaty have the largest influence and are the least flexible to short run adjustment.

The objective function chosen for this analysis was a simple maximization of beneficial use, defined by Equation (3A). This equation is maximized subject to the remaining equations including the economic benefits Equation (A10). That is, approximately consistent with the Law of the River, the model maximizes beneficial use, while tracking economic impacts.

The text results report on a *simulated* economic impact produced by the minnow constraint, not on an *optimized* economic impact. For policy analysis conducted under the situation of minnow flow requirements at the San Acacia reach, the minnow flow constraint is added. Without the minnow flow requirements, the constraint is deleted.

An important avenue for further research is to examine measures to minimize the economic cost of protecting instream flows for the minnow. A least cost policy for delivering minnow flows requires two steps. First the minnow flow constraint is enforced. Second the beneficial use objective in Equation (A3) is changed to the economic objective in Equation (A10).

Where water could be allocated by a market like institution, such as a water bank that transferred water from lower valued to higher valued uses, results are simulated by maximizing economic benefits defined by Equation (A10). In practice, we found that operating the model produces a small feasible

space and that we were fortunate when a feasible solution occurs for the complete 44-year analysis. Given the small size of the feasible space, we discovered that the choice of an objective had virtually no effect either on water use patterns or on total economic benefits produced by those use patterns.

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