Market Exchange Impact on Water Supply Planning with Water Quality

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Abstract: A market-based water supply problem is modeled as an optimization problem maximizing net benefit from water use such that all the concerned parties use an economically optimal allocation considering damages due to total dissolved solids (TDS) and institutional constraints. These institutional constraints include water supply requirements under international treaty and historical allocations of water to agriculture. The income from water in municipal use, based on the concept of consumer surplus, is utilized in the objective function along with benefit from agricultural uses, supply costs, and damage costs due to poor quality water, which are estimated using available data. The research assesses the impact that system-wide optimal allocation of water will have in increasing monetary benefits and reducing water salinity levels in terms of TDS along the reach of the Rio Grande from Elephant Butte, New Mexico, to Fort Quitman, Texas. The analysis is performed under three institutional constraints, which include flow regulation at the reservoir, restrictions on trade between states, and allowing trade between the states. Among these scenarios, allowing trade between the states results in the best solution in terms of both net benefit and reducing damage due to poor quality water.

DOI: 10.1061/(ASCE)0733-9496(2004)130:6(439)

CE Database subject headings: Water supply; Water quality; Water use; New Mexico; Texas.

Introduction

This research assesses the economic benefits and impact on water quality of system-wide optimal allocation of water in the Rio Grande Project, which consists of the Elephant Butte Reservoir and its associated 320 km (200 mi) of canals in southern New Mexico and western Texas. Currently, water allocation is restricted to certain historical uses and legal entities—particularly irrigation districts. Because of projected water deficits, particularly in groundwater supplies, municipal entities will need to acquire additional surface water supplies. The emphasis of the study concerns the impact that system-wide market allocation of water will have on reduced water salinity levels in terms of total disolved solids (TDS) along the reach of the Rio Grande from Elephant Butte, New Mexico, to Fort Quitman, Texas. Market allocated water reduces levels of TDS to which agriculture, urban use, and riparian habitat are exposed.

The project is a series of dams and canal systems on and along the Rio Grande and the only surface water supply in this arid region. The Elephant Butte Reservoir with a storage capacity of 2.6 billion m^3 (2 million acre-ft) is the primary feature of the project, which consists of approximately 52,610 ha of irrigated agriculture; the rapidly growing cities of El Paso, Texas; Las Cruces, New Mexico; Ciudad Juarez, Mexico; and other smaller cities and towns. The combined population in the area is in excess of 2 million. The Percha, Leasburg, and Messilla diversion dams serve acreage in the Elephant Butte Irrigation District (EBID) in New Mexico; whereas, American and Riverside diversion dams serve the El Paso County Water Improvement District (EPCWID) No. 1 in Texas. These diversion dams are scattered over the project region and serve specific irrigation areas in their respective irrigation districts, which are located in Rincon, upper Messilla, lower Messilla, upper El Paso, and lower El Paso valleys.

Historically, project water has been allocated for agriculture with an annual release of approximately 975 million m^3 (790,000 acre-ft). All water, except 74 million m^3 (60,000 acre-ft) allocated by treaty to Mexico (7% of the annual release), goes to two irrigation districts: EBID and EPCWID No. 1. These two irrigation districts receive approximately 514 million m^3 (416,000 acre-ft or 57%) and 387 million m^3 (314,000 acre-ft or 43%) of the total release to irrigation districts, respectively. Municipal water utilities serving urban areas have relied on groundwater; however, population growth has greatly increased depletion to the point that the viability of underlying aquifers are a serious concern, resulting in a constraint to future growth. In response to the depletion of groundwater aquifers, cities proximate to the project have developed groundwater conservation plans. Although these plans typically call for reduced water use by urban end-users, population growth will necessitate that cities secure additional surface water supplies. Table 1 projects surface water use for El Paso and Las Cruces with the assumption that neither of these cities can increase their level of groundwater pumping (Boyle Engineering Corp. and Parsons Engineering Science, Inc., unpublished report to the New Mexico-Texas Water Commission).

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Note. Discussion open until April 1, 2005. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on July 29, 2002; approved on December 4, 2003. This paper is part of the ***Journal of Water Resources Planning and Management***, Vol. 130, No. 6, November 1, 2004. ©ASCE, ISSN 0733-9496/2004/6-439–449/$18.00.

Table 1. Rio Grande Project Annual Urban Water Use (acre-ft)

	1998			2043		
Year	Total	Surface	Ground	Total	Surface	Ground
El Paso	135,733	58,741	76,992	405,319	355,319	50,000
Increased surface water use					296,578	
Las Cruces	20,020	0	20,020	96,116	75,916	20,200
Increased surface water use					75,916	

Salinity and other contaminants build up in the water of the Rio Grande as it is used and reused. Irrigation return flow decreases water quality and presents a problem to downstream users because a portion of the water supply returns to the river, carrying high levels of TDS that affect the water quality of the mainstream flow system downstream. The drainage water first infiltrates into the subsurface aquifer, after which it flows to the mainstream with a fairly uniform TDS content approximated at about 1,500 ppm. One of the difficulties of using Rio Grande water for urban purposes is that high salinity and other pollutants in the water will require costly treatment to reduce economic damages and meet the U. S. Environmental Protection Agency (EPA) recommended safe drinking water standards of a maximum TDS of 1,000 ppm. By the time the Rio Grande reaches El Paso and Juarez, salinity concentrations are high enough to cause economic damages and exceed EPA recommended standard as a source of drinking water, Fig. 1. Fig. 2 indicates the historical flows in the Rio Grande Project.

Objective

Under current allocation policies and institutions, the irrigation districts are the primary beneficiaries of the Rio Grande Project water. A market-based reallocation will guarantee that original water users be protected as priority water-right holders but that other users can purchase necessary water at market prices. One of the unresolved issues is the implication of such a reallocation on water quality in the system. Regulations by EPA and local agencies recommend that the TDS level be maintained below 1,000 ppm. As indicated in Fig. 1, salinity levels during the off irrigation season reach higher levels than the 1,000 TDS standard. For this water to be used for municipal purposes, it requires very expensive treatment to reduce salinity levels. The objective here is to model the Rio Grande water-supply system as a market-based allocation of water. It is formulated as an optimization problem maximizing net benefit from water use in the system such that all the concerned parties get an economically optimal allocation, given the following constraints: (1) the water requirement under the international treaty is satisfied; (2) minimum requirements for industrial purposes are satisfied; (3) the net benefit from irrigation and municipal water supplies is maximized; and (4) the TDS damage is minimized. As noted by Burness and Quirk (1979), an economically efficient optimal allocation of water approximates the allocation that occurs with well-defined water rights and leasing of project waters.

Several studies have been done on the Rio Grande Project by different agencies and consulting firms, including those by Engineering-Science, Inc. (1991a,b) and jointly by Boyle Engineering Corp. and Parsons Engineering Science, Inc. (unpublished report, 1988). The general approach utilized in these studies is to identify and assess different management alternatives for the project using available data so that the alternative that resulted in the best management may be selected. Engineering-Science, Inc. (1991) has assessed various opportunities for water storage facilities and the possibilities of additional water supplies by transmountain diversion and by salvage of losses so that water shortages in the project region are overcome. The study by Boyle Engineering Corp. and Parsons Engineering Science, Inc. (unpublished report, 1998) has been aimed at drain mitigation strategies so that acceptable water quality is maintained for the downstream users in the project area. According to the studies, almost all selected strategies reduce the problem of quality issues to some extent. However, the studies do not consider the formulation of the problem as a single optimal problem.

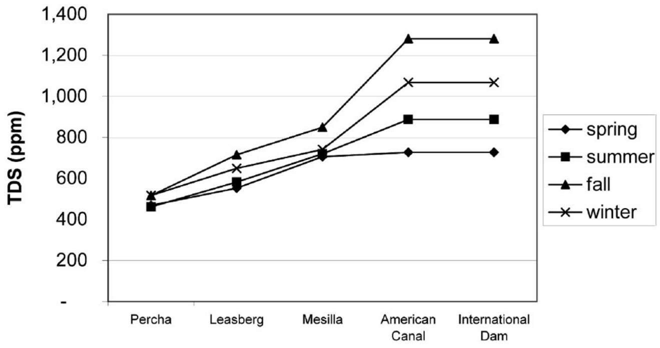

Fig. 1. Historical total dissolved solids (TDS) levels in the Rio Grande Project (Source: Boyle Engineering Corp. and Parsons Engineering Science, Inc., unpublished report, 1998)

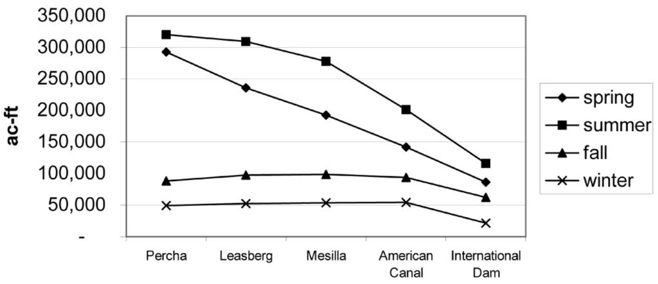

Fig. 2. Historical flows by season (Source: Boyle Engineering Corp. and Parsons Engineering Science, Inc., unpublished report, 1998)

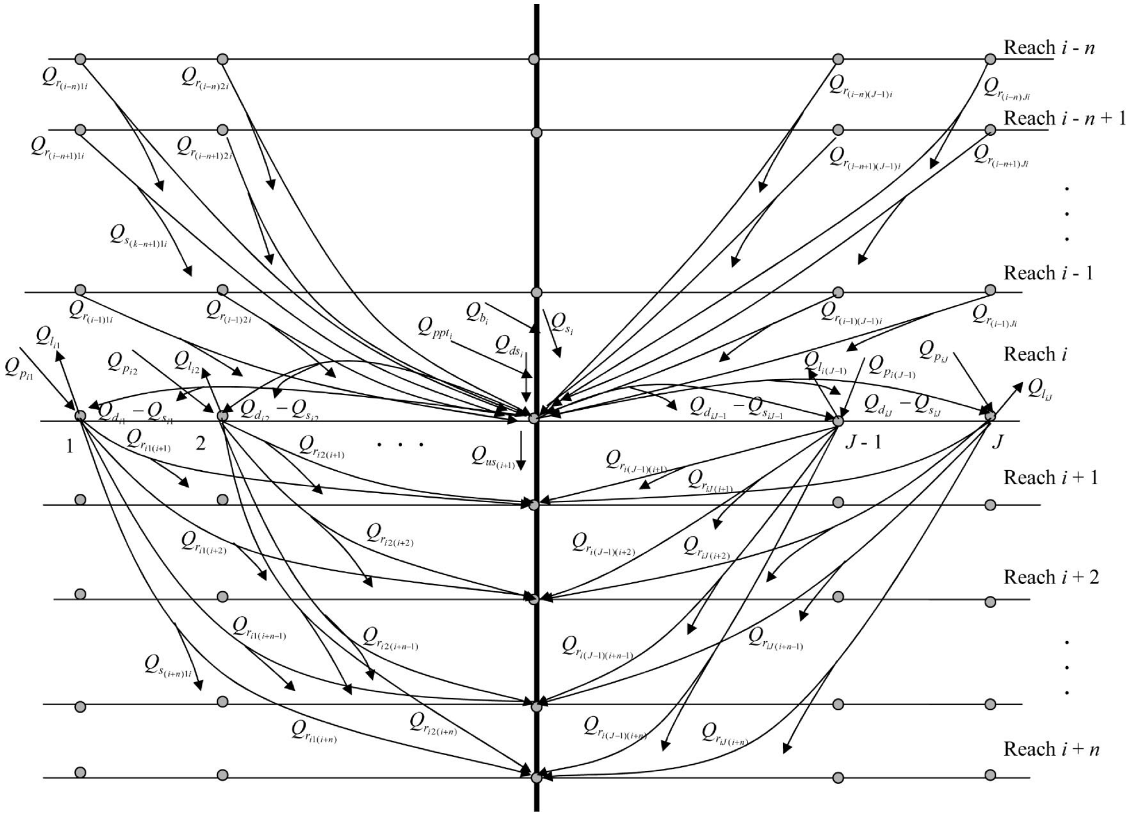

Fig. 3. Schematic representation of the hydraulics of a typical watershed

Model Formulation

A general problem on a regional or watershed scope is considered and all the water users in the watershed are first identified. The general water- supply customers include municipalities, industry, hydropower, irrigation, ranching, recreation, aquaculture, environmental protection, remediation, and so on; whereas, general water sources include instream flow, groundwater pumping, precipitation, interbasin transfer, and return flow or drainage. Thus, the watershed is divided into a total of I reaches, where the delineation of a reach is based on whether there is one or more diversions and/or one or more return flows at only one "point" in the reach (Fig. 3). In each reach, a total of J activities are considered.

Continuity Equations

An arbitrary reach i in Fig. 3 is considered to develop the continuity or mass conservation equations. In this figure, all the possible flows associated with reach i are indicated. The point of diversion, or return, in the reach is the subject of the continuity equations, expressed as

$$\sum_{k=(i-n)}^{i-1}\sum_{j=1}^{J}(Q_{r_{kji}}-Q_{s_{kji}})+Q_{ds_i}-\sum_{j=1}^{J}Q_{d_{ij}}-Q_{us_{(i+1)}}=0 \qquad (1)$$

where $Q_{r_{kji}}$=the return flow from demand point j in reach k to reach i ($k \neq i$); $Q_{s_{kji}}$=the seepage loss in the return flow from demand point j in reach k to reach i ($k \neq i$); $Q_{d_{ij}}$=the diverted flow from reach i for demand point j, where j represents any kind of demand for water ($i=1,2,\ldots,I, j=1,2,\ldots,J$); Q_{ds_i}=the flow at the downstream end of reach i, that is, instream flow into the point of diversion in reach i, referred to herein as a node; Q_{us_i}=the flow at the upstream end of reach i; and n=the maximum number of reaches a return flow travels before draining into the main stream. The same equation holds true for the other reaches, with some adjustment for boundary conditions for the return flows near the upstream and the downstream ends of the watershed. Also, for each demand point, the following continuity equation can be derived:

$$Q_{d_{ij}}-Q_{s_{ij}}+Q_{p_{ij}}-Q_{l_{ij}}-\sum_{k=(i+1)}^{i+n}Q_{r_{ijk}}=0 \qquad (2)$$

for all i and j where $Q_{s_{ij}}$=the seepage loss in reach i on the way to demand point j; $Q_{p_{ij}}$=the pumped flow of groundwater from reach i for demand point j; and $Q_{l_{ij}}$=the consumptive use in reach i at demand point j. Within each reach, the following continuity equation governs:

$$Q_{us_i}+Q_{b_i}+Q_{ppt_i}-Q_{ds_i}-Q_{s_i}=0 \qquad (3)$$

for all i where Q_{b_i}=the interbasin transfer to reach i; Q_{ppt_i}=the flow into reach i accountable to net precipitation contribution; and Q_{s_i}=the instream seepage loss in the stream in reach i.

Water Quality Equations

A quality parameter considered in this study is the TDS in the water supplied. Generally, however, multiple water-quality parameters may be considered because the other constituent equations are similar. The quality constraint for the point of diversion in reach i is expressed as

$$\sum_{k=(i-n)}^{i-1}\sum_{j=1}^{J} C_{r_{kji}}(Q_{r_{kji}}-Q_{s_{kji}}) + C_{ds_i}Q_{ds_i} - C_{w_i}\left[\sum_{j=1}^{J} Q_{d_{ij}} + Q_{us_{(i+1)}}\right] = 0 \tag{4}$$

where $C_{r_{kji}}$ represents the quality parameter in the return flow from demand point j in reach k to reach i $(k \neq i)$; C_{ds_i} represents the quality parameter in Q_{ds_i}; and C_{w_i} represents the weighted quality parameter in $Q_{d_{ij}}$ or $Q_{us_{(i+1)}}$. The flow out of the nodes will have the same quality assuming "perfect" mixing conditions (Yang, et al. 1999), which can be expressed as

$$C_{w_i} = C_{d_{ij}} = C_{us_{(i+1)}} \tag{5}$$

Defining $C_{w_{ij}}$ as the weighted quality parameter at any demand point j in reach i, the constraints for demand point j can be expressed as

$$C_{d_{ij}}(Q_{d_{ij}}-Q_{s_{ij}}) + C_{p_{ij}}Q_{p_{ij}} - C_{w_{ij}}\left[Q_{l_{ij}} + \sum_{k=(i+1)}^{i+n} Q_{r_{ijk}}\right] = 0 \tag{6}$$

for all i and j. Similar equations can be also derived for the instream flow in each reach as

$$C_{us_i}Q_{us_i} + C_{b_i}Q_{b_i} + C_{ppt_i}Q_{ppt_i} - C_{ds_i}Q_{ds_i} - \left(\frac{C_{us_i}+C_{ds_i}}{2}\right)Q_{s_i} = 0 \tag{7}$$

for all i. Note that the average TDS concentration is used for the seepage loss in reach i assuming that the change in the concentration in the reach is approximately linear.

Flow Regulation

In Fig. 3, the flow system represents the general scenario in which diversions and pumping in any reach and return flows from any reach to any other reach downstream are possible. However, this may not be the case in practice because, for instance, the number of demand points in one reach may not be equal to those in other reaches. Introducing coefficients with values of 0 or 1 for each of the arcs can regulate these flows, where 0 is used to turn off and 1 is used to turn on a flow along a given arc. The instream flows Q_{us_i} and Q_{ds_i} do not require the 0 or 1 coefficients because these flows always exist. A similar approach of using binary variables for turning off and on flow arcs has been used by Ward et al. (2001). The use of such coefficients has advantages in sensitivity analysis to the optimization model. All uncertain activities can be turned on or off in the model and their results evaluated.

Let $K_{d_{ij}}$ be the coefficient of flow for $Q_{d_{ij}}$, $K_{p_{ij}}$ be the coefficient of flow for $Q_{p_{ij}}$ and so on. Then, the above continuity and TDS equations are modified as follows:

$$\sum_{k=(i-n)}^{i-1}\sum_{j=1}^{J} (K_{r_{kji}}Q_{r_{kji}} - K_{s_{kji}}Q_{s_{kji}}) + Q_{ds_i} - \sum_{j=1}^{J} K_{d_{ij}}Q_{d_{ij}} - Q_{us_{(i+1)}} = 0 \text{ for all } i \tag{8}$$

$$(K_{d_{ij}}Q_{d_{ij}} - K_{s_{ij}}Q_{s_{ij}}) + K_{p_{ij}}Q_{p_{ij}} - K_{l_{ij}}Q_{l_{ij}} - \sum_{k=(i+1)}^{i+n} K_{r_{ijk}}Q_{r_{ijk}} = 0 \text{ for all } i \text{ and } j \tag{9}$$

$$Q_{us_i} + K_{b_i}Q_{b_i} + K_{ppt_i}Q_{ppt_i} - Q_{ds_i} - K_{s_i}Q_{s_i} = 0 \text{ for all } i \tag{10}$$

$$\sum_{k=(i-n)}^{i-1}\sum_{j=1}^{J} C_{r_{kji}}(K_{r_{kji}}Q_{r_{kji}} - K_{s_{kji}}Q_{s_{kji}}) + C_{ds_i}Q_{ds_i} - C_{w_{ij}}\left[\sum_{j=1}^{J} K_{d_{ij}}Q_{d_{ij}} + Q_{us_{(i+1)}}\right] = 0 \text{ for all } i \tag{11}$$

$$C_{d_{ij}}(K_{d_{ij}}Q_{d_{ij}} - K_{s_{ij}}Q_{s_{ij}}) + C_{d_{ij}}K_{p_{ij}}Q_{p_{ij}} - C_{w_{ij}}\left[K_{l_{ij}}Q_{l_{ij}} + \sum_{k=(i+1)}^{i+n} K_{r_{ijk}}Q_{r_{ijk}}\right] = 0 \text{ for all } i \text{ and } j \tag{12}$$

$$C_{us_i}Q_{us_i} + C_{b_i}K_{b_i}Q_{b_i} + C_{ppt_i}K_{ppt_i}Q_{ppt_i} - C_{ds_i}Q_{ds_i} - \left(\frac{C_{us_i}+C_{ds_i}}{2}\right)K_{s_i}Q_{s_i} = 0 \text{ for all } i \tag{13}$$

$$C_{w_i} - C_{d_{ij}} = 0 \quad \text{for all } i \text{ and } j \tag{14}$$

$$C_{w_i} - C_{us_{(i+1)}} = 0 \quad \text{for all } i \tag{15}$$

$$C_{w_{(i-1)}} - C_{ds_i} = 0 \quad \text{for all } i \tag{16}$$

Additional Constraints

Apart from the mass balance constraints, other physical and resource constraints affect the system. The capital expenditure available for pumping the water and the amount that can be pumped may be limited. Environmental regulations may require that the TDS level at any point be kept below some acceptable level. Such constraints generally can be given as

$$K_{p_{ij}}Q_{p_{ij}} \leqslant A \tag{17}$$

$$C(K_{p_{ij}}Q_{p_{ij}}) \leqslant B \tag{18}$$

$$K_{w_{ij}}C_{w_{ij}} \leqslant C \tag{19}$$

where A = a constant; B = a constant or a function of the amount of pumped water; C = a constant or a function of the quality parameter in the supplied water; and $C(K_{p_{ij}}Q_{p_{ij}})$ = the cost of pumping at demand point j in reach i.

Objective Function

The objective function can be expressed in terms of the net benefit from the water resources allocated at each of the demand points, the costs associated with each allocation, and the damages from TDS levels at each point. Defining $P(Q_{d_{ij}}, Q_{p_{ij}})$ as the profit of allocated supplies (both surface and groundwater), $C(Q_{d_{ij}}, Q_{p_{ij}})$ as the cost of allocation, and $D(C_{d_{ij}}, C_{p_{ij}}) = D(C_{w_{ij}})$ as the damage from salinity, the objective is to maximize the net profit Z, given as

$$Z = P(Q_{d_{ij}}, Q_{p_{ij}}) - C(Q_{d_{ij}}, Q_{p_{ij}}) - D(C_{w_{ij}}) \tag{20}$$

subject to constraint Eq. (8)–(19).

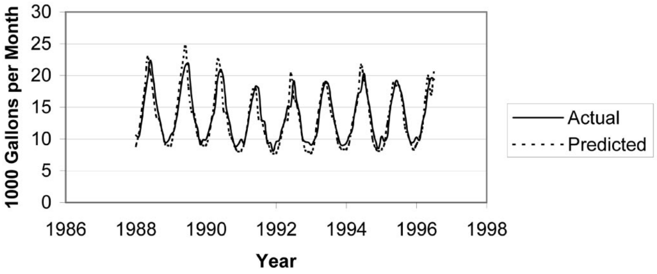

Fig. 4. Predicted versus actual monthly household water use in El Paso (Source: Based on results by Michelsen et al. (1998)

Model Application

The model developed is applied to the Rio Grande Project by considering seasonal time frames. Groundwater and Caballo reservoir's average annual release are the water sources; whereas, water requirements for irrigation and municipal purposes are primary demands.

Surface Water Release and Drought Scenario

Although the 790,000 acre-ft per year release from Caballo Reservoir is the full allocation, with 60,000 acre-ft of it reserved for Mexico, releases have historically been variable, particularly if there is a spill or limited storage. To assess the impact of limited release, we assume a 50% reduction in water to 395,000 acre-ft with 60,000 acre-ft still allocated to Mexico. This limited release scenario is explained in the "Model Results" section.

Municipal Value of Water

The net benefit of water in municipal use is the integral of water demand (consumer surplus) minus the cost of supply and distribution. Griffin (1990) outlines a methodology for measuring consumer surplus of municipal water, which is used here. The analysis uses estimates of water demand by Michelsen et al. (1998). The parameters for the city of Las Cruces are in this report. By using data for the independent variables from the city of El Paso, the model predicts with a high degree of accuracy. With the El Paso rate structure, the model estimates that overall water demand has −0.115 demand elasticity. Fig. 4 shows the predicted dependant residential monthly consumption plotted against the actual use in El Paso for 1988 to 1996. Note that this is an out-of-sample comparison. The functional form of the return is given as

$$R = aQ - \left(\frac{b}{N}\right)Q^2 \tag{21}$$

where R = the return in dollars/year; Q = the yearly domestic water supply in acre-ft; N = the number of households in the city/town; and a and b = constants. The number of households in El Paso is approximately 120,000, based on the number of water accounts with El Paso Water Utility (EPWU). Hatch, Las Cruces, and Anthony have accounts of 1,000, 19,000 and 2,000, respectively. Hatch, Las Cruces, and El Paso are located in the Rincon, Mesilla, and El Paso valleys, on the opposite sides of the irrigation areas of Percha, Leasburg, and El Paso, respectively. Anthony is located in the Mesilla Valley, below the Mesilla irrigation area. Table 2 gives the values of a and b for different towns/cities in the project area.

Table 2. Values of a and b in Eqs. (21) and (25) for Different Cities in Project Area (1999/2000 Estimates)

S Number	Town/city name	a value	b value	Number of households	b/N value
1	Hatch	8,948	7,480	1,000	−7.479
2	Las Cruces	21,604	18,050	19,000	−0.950
3	Anthony	8,948	7,480	2,000	−3.739
4	El Paso	8,948	7,480	12,0000	−0.062

The costs of supply and distribution of municipal water are obtained from a previous analysis by Boyle Engineering Corp. (1992). The cost of processing surface water for domestic consumption (surface water treatment and distribution) is estimated at $503.7/ acre-ft; whereas, the cost of supplying groundwater to the towns/cities (limited treatment and distribution) is estimated at $325/ acre-ft per year (Boyle Engineering Corp. 1992). These costs and the consumption benefits from Eq. (21) result in net benefits.

During periods of drought, the value of water will obviously increase. As long as water can be allocated to agriculture, the value in use of those activities will determine marginal water values and prices in a water market. However, at some point, water can only be allocated to the urban sector, and reductions in that sector will take place. Here there is a trade-off between water reductions for the user (loss of consumer surplus) versus the cost of external supplies. By using estimates of the cost of external water sources (desalination and water import reported in the Boyle analysis), we are able to impute water values during these periods.

Agricultural Use

Agriculture is the dominant user of water in the project and thus determines the economic value at the margin. If industry and cities cannot obtain water through market purchases to provide for growth in consumption, then the value of water increases dramatically. However, as long as a city such as El Paso can procure the water it needs, the value of water at equilibrium has the value in agricultural use. Using cost and return data from the New Mexico Cooperative Extension and Texas A&M University, the model derives the economic value of water in agriculture. The value of water is assumed as the residual return after all other costs are paid. For example, a crop may have $1,000 total return per acre and $900 of non-water expenses, leaving a $100 residual value that can be attributed to water availability. If the crop uses 3 acre-ft per acre, the value of water is about $33/acre-ft. An important factor in the value of water is the role of fixed costs. A farmer has extensive capital investment in farm equipment, irrigation systems, land, and other improvements. If the farmer leases water for a short period, he will essentially idle the other capital associated with farming. He certainly will not lease his water unless he gets a return for both water and idled capital. On a longer time frame, say a lease of 20 years or the permanent sale of water, the farmer may sell farm equipment, even sale the land, and not require a payment for these factors of production. The long-run value of water is less than the short run. Another complicating factor is land tax implications for idling cropland by selling off water. Agricultural production receives favorable tax assessment rates. If an agricultural water user sells or leases water for a long period of time, he loses his agricultural tax status.

The income from the irrigation water supply results from the

Table 3. Agricultural Value of Water by Crop in EBID and EPCWID

Irrigation district		Grains	Cotton	Chile	Pecans	Forage	Average
EBID	Acreage	4,550	17,048	17,459	13,767	24,240	—
	Benefit ($/acre)	$60	$126	$278	$300	$350	$258
	Water per acre (acre-ft)	2.5	3	5	5	5	4.4
	Value per acre-ft ($)	$24	$42	$56	$60	$70	$59
	Accumulated water use (acre-ft)	11,375	62,519	149,814	218,649	339,849	—
EPCWID	Acreage	6676	11,968	1464	5047	11331	—
	Benefit ($/acre)	$65	$133	$253	$287	$319	$205
	Water per acre (acre-ft)	2.5	3	5	5	5	3.9
	Value per acre-ft ($)	$26	$44	$51	$57	$64	$53
	Accumulated Water use (acre-ft)	16,690	52,594	59,914	85,149	141,804	—
Total water use		28,065	115,113	209,728	303,798	481,653	—
Marginal value per acre-ft		$25	$43	$53	$59	$67	—

two major irrigation districts within the project region: EBID and EPCWID No. 1. The average yearly return from the EBID district is estimated to be about $258 per acre of land, which needs a total of 4.4 acre-ft of water per year. Of this water requirement, 3 acre-ft of water is usually obtained from diverted surface water from the Rio Grande and 1.4 acre-ft of water from aquifers pumped in the vicinity of the irrigation area, which then has a direct effect of reducing the flow in the main channel. For EPCWID No. 1, the average return per acre of land irrigated is $205/ year, (Table 3). The corresponding amount of water delivered to farms is 3 acre-ft.

The value of water in agriculture is based on average crop returns, not marginal returns. The urban values, however, so dominate the solution that agriculture becomes simply a residual claimant. With a slow evolution to a market allocation of water, it is expected that more marginal valued crops will be reduced first (cotton and grains with 18 and 37% of water use in EBID and EPCWID, respectively) as water is converted from agriculture to urban uses; whereas, higher valued crops (pecans, chilies, and alfalfa) will be reduced last. Reviewing the net returns for these lower valued crops (Libbin 2002), the value of water in use is about $43/ acre-ft for both districts in grains and cotton. When these agricultural uses are completely retired, the marginal value of water in use will increase to approximately $65/ acre-ft. Table 3 gives the incomes from different crops and the weighted average return per acre of irrigated land and the value per acre-ft in each crop type. Because agriculture is the residual claimant, it is possible to estimate the opportunity cost associated with water from the values indicated above and potential market prices that might exist. The price scenarios that are reported in the results section employ the concept of local marginal pricing used in electricity (Hogan 1992). For major nodes along the river, demand for water diversion is increased by 1 acre-ft. The local marginal price is then measured as the change in the overall objective function, Eq. (20), compared to the solution without the 1 acre-ft increase.

All the water for irrigation purposes in EPCWID is obtained from surface water. Because of its adverse salinity effect on crop growth, groundwater is not used for this irrigation district. Differences in net income between the two districts may be due to the salinity impact on crop yield, but there is not sufficient data to analyze the complete salinity effect as described below. Costs of district supply and distribution are based on EBID and EPCWID No. 1 revenue requirements and the assumption of nonprofit.

Economic Damages from Saline Water

The economic damage that results from supplying saline water to domestic uses and irrigation districts is generally small, but appreciable. The damage results from the reduced lives of household appliances such as dishwashers, water heaters, food waste disposers, water softeners, and evaporative coolers (Darn et al. 1988; Ragan 2000). In the towns/cities that are present in the study area, the damage caused by salinity is estimated at 3 cents per household per ppm of TDS per year. TDS damage is expressed as

$$D = 0.03NC(Q) \tag{22}$$

where D=the damage in dollars per year; N=the number of households for which Q is supplied; and $C(Q)$=the TDS concentration in Q. Damage to crops because of the salinity of the irrigation water occurs in the form of reduced yield of irrigated crops caused by toxic and osmotic effects (Ayers and Westcott 1989). Salinity damage to agricultural production is estimated using an equation developed by Maas and Hoffman (1977), which is given as

$$Y = 100 - \alpha(EC_s - \beta) \tag{23}$$

where Y=relative yield to maximum potential; α and β are crop-specific coefficients; and EC_s=soil salinity measured by electric conductivity (deciSiemens per meter, dS/m). Soil salinity is related to irrigation water salinity by employing a leaching fraction in irrigation. We assume a 12% leaching fraction for irrigation practices in the two districts. With this fraction, soil salinity is related to irrigation water salinity by the equation

$$EC_s = 0.2EC_w(1 + 1/LF) \tag{24}$$

where LF=the leaching fraction and EC_w=the salinity of irrigation water. The model keeps track of TDS, which is linearly related to EC_w by a factor of 650. Aggregate loss functions are developed for the irrigation districts by summing individual crop-losses weighted by historical crop-acreage percentages. One factor that is not included in the model is the degree that salinity has

Table 4. Approximate Demand Proportions by Different Activities at Rio Grande Project

Activity	December—February	March—May	June—August	September—November
Municipal (fractions)	0.15	0.25	0.35	0.25
Agricultural (unit proportions)				
Diversion	—	0.30	2.20	0.50
Pumping	—	1.50	0.50	—
Subtotal	—	1.80	2.70	0.50

changed cropping patterns between EBID and EPCWID No. 1. EBID has greater acreage percentages of alfalfa, chili, onions, and lettuce. These are high return crops but are sensitive to salinity levels above 1,000 ppm TDS. EPCWID No. 1's low acreage percentages possibly reflect the effects of salinity, but there are many other factors that determine crop selection. Salinity damage does not occur at levels below 500 ppm for the crops grown in the project. Thus, the relevant range for damage is over 500 ppm of TDS level. Annual damages to EPCWID No. 1 are estimated at \$0.044/acre, per unit increase in TDS over 500 ppm.

Reach Definition

The project area is subdivided into a total of 17 reaches. In each reach, five water uses are considered, namely, the point of diversion, two potential irrigation areas (one on each side), and municipal and industrial purposes. At each demand point in a reach, water supply is obtained from diverted water or from pumping, except for agricultural purposes in reaches 12 and 15 where groundwater is too saline for this purpose. The model specifies return flows from each demand point to the stream as far downstream as four reaches below the reach. Pumping for municipal and industrial purposes is from deeper groundwater with a TDS level of approximately 250 ppm. The source of pumped water for irrigation at the Percha, Leasburg, and Mesilla irrigation areas is from shallow groundwater with a TDS level of approximately 1,500 ppm. Before the diverted water reaches the point of use for irrigation, a significant amount of seepage loss occurs. Although this water is a loss to the immediate purpose for which it is diverted, it will find its way back to the river as a drainage flow or percolate deep into the groundwater storage. For this analysis, 45% for EBID and 55% for EPCWID of the water diverted for irrigation purposes is lost and becomes seepage flow, eventually draining back to the river. The return flows from the municipalities take place through conduits, and thus, there is negligible seepage loss.

At each of these demand points, the consumptive use depends on the type of use. In agricultural areas, this constitutes the evapotranspiration; whereas, at the municipal points of use, it constitutes the consumptive uses for purposes such as drinking, cooking, and so on. For industrial use, it constitutes the amount that is used in the industrial byproduct. To account for these effects, it is assumed that about 50% of the water used for irrigation and municipal purposes and about 70% of the water used for industrial purposes are consumptively used. The remaining water from each point of use drains back into the river.

The seasonality of the management of the project results from activities that occur only during certain seasons of the year. The irrigation activities occur during the spring, summer and fall seasons. For each city/town, urban water demand magnitude depends on the season; it is maximum during the summer season and minimum during the winter season. Therefore, the planning year is divided into four seasons, and the problem is formulated as an NLP problem. The seasons considered include December to February, March to May, June to August, and September to November as seasons 1, 2, 3, and 4, respectively. The approximate seasonal demand proportions by the different activities are given in Table 4.

The general form of the objective function for urban water demands is the sum of the seasonal demands. For the cities/towns, the income (benefit) from the supply is expressed as

$$a[Q(S_1)+Q(S_2)+Q(S_3)+Q(S_4)] - \frac{b}{N}[Q(S_1)+Q(S_2)+Q(S_3)+Q(S_4)]^2 \tag{25}$$

where $Q(S_z)$ denotes the demand during season z where $z=1$, 2, 3, or 4. The other parameters are as defined earlier. Note that Eq. (25) is the same as Eq. (21) except that the total yearly demand is substituted by the sum of the four seasonal demands. For agricultural activities, it is assumed that the total income is generated only during the harvesting season, i.e., season 4. However, water demands for this purpose prevail during the last three seasons. Thus, the total income per acre of land in the agricultural areas is \$266 in reaches 1, 4, and 7 and \$187 in reaches 12 and 15. Similarly, the water-supply costs and the TDS damages used in the objective function are taken as the sum of the seasonal costs and damages. The yearly cost of supplying surface water and groundwater to the towns/cities are taken as \$503.7 and \$325/acre-ft, respectively. The cost of supplying water from the river to the irrigation districts is \$15/acre-ft for the last three seasons of the year, i.e., during the diversion seasons. Similarly, the cost of supplying groundwater to the irrigation districts is estimated at \$10/acre-ft during the two seasons of pumping to the irrigation districts. The seasonal TDS damages that result from both the urban and the irrigation supplies are approximated by assuming the same proportionate values as the seasonal demands (see Table 4). Thus, the seasonal urban TDS damages per parts per million are 0.45, 0.75, 1.05 and 0.75 cents during seasons 1, 2, 3, and 4, respectively. Similarly, the estimated irrigation TDS damages per parts per million are 1.6, 2.4, and 0.4 cents for the last three seasons, respectively.

Total drainage flow from the agricultural activities is spread over two seasons, with about 75% of the drainage occurring during the same season as the diversion season and the remaining 25% of the drainage occurring during the subsequent season. No diversion or pumping activity for irrigation exists during the winter season. However, there is carryover drainage during this season from the diversion during the fourth season of the previous year. Because the drainage from the municipal and industrial activities take place in conduits, it is assumed to occur during the same season of diversion and pumping. To write this distribution of drainage flows over two seasons in equation form, let $Q_{lm(zij)}$ be the return flow from reach i from the diversion for purpose j

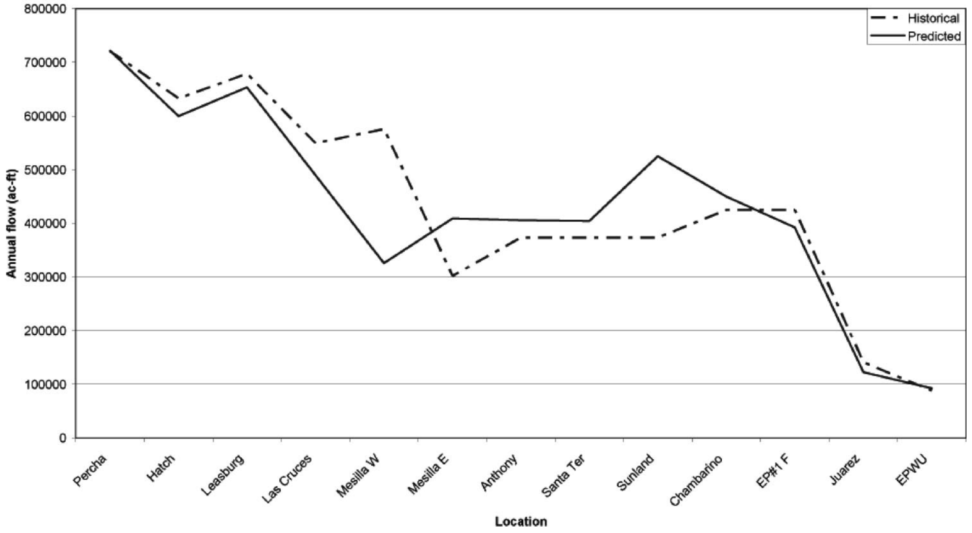

Fig. 5. Historical annual river flow versus flow predicted by model (2003)

during season m and returning during season z to l reaches downstream. Then, the two general drainage flow distributions over two seasons can be given as

$$Q_{lm(zij)} = 0.75[Q_{lm(zij)} + Q_{l(m+1)(zij)}] \tag{26}$$

$$Q_{l(m+1)(zij)} = 0.25[Q_{lm(zij)} + Q_{l(m+1)(zij)}] \tag{27}$$

To better illustrate the notations used here, consider, for instance, $Q_{22(S2,R1,A1)}$. This is the return flow from reach 1 ($R1$) from the diversion for agricultural activity 1 ($A1$) during season 2 and returning during the same season ($S2$) to two reaches downstream.

Institutional Constraints

There are three institutional constraints that affect the operation of the system: (1) Water is only released during the irrigation season, flow in the river channel during the off-season being entirely return flow; (2) Water can not be traded between states; a farmer in New Mexico has no mechanism for selling water to the city of El Paso; and (3) The current allocation of water in Elephant Butte is designated as 57% to EBID and 43% to EPCWID No. 1. A special agreement with the U.S. Bureau of Reclaimation (USBR) allows EPCWID to sell water to municipalities on the Texas side of the border.

Institutional constraints have been incorporated into the model in terms of release amounts at the dam, flow requirements at the Texas border, and allowable use of surface water by municipalities. The effects of the constraints are compared against an unconstrained model to assess the economic implications of the constraints. There are three scenarios considered: (1) water is not released during the off irrigation season and water trade can only occur intrastate; (2) water can be released seasonally, but it can not be purchased by El Paso from New Mexico interests; (3) water can be released according to demand during the year and all parties are allowed to trade water rights. The model formulation was prepared as a GAMS/MINOS input code and was solved using the latest release (version 2.50) of GAMS/MINOS software (GAMS Development Corp, Washington, D.C.).

Time Period

The model is intertemporal only in a seasonal context; however, municipal demand can be projected for population growth. The model can be optimized for a specific future year given a population projection. The El Paso and Las Cruces municipal areas have been growing at 2% per year, which doubles their respective populations in approximately 36 years. The water supply issue is cast mainly in future terms. As such, the results are analyzed for the year 2040 when El Paso and Las Cruces have more than doubled in size. Other municipalities are assumed to grow at the same rate.

Model Results

Fig. 5 indicates the model track of river flows compared to historical average flows. With some minor variations, the model captures the general trend of water in the channel as it is released from Elephant Butte Dam and flows down the Rio Grande past El Paso. Table 5 outlines the gross and net benefits of water operations under the three scenarios. The table also indicates salinity damages.

No Trade or Winter Release

This is the baseline scenario, which shows very little change in water use for agriculture. Municipalities, particularly El Paso, must obtain expensive water from other sources. The costs of such water supplies are considerable thus leading to lower net benefit. Seasonally, water flows and TDS levels do not change from historical conditions. The objective function for this scenario (the baseline) is $501 million annually.

Restricted Trade and No Winter Release

In this scenario, urban water users in Texas can purchase water from EPCWID No.1. In New Mexico, urban water users can purchase from EBID. Because there is no joint agreement in water use, Elephant Butte Dam operating rules continue to allow only for spring and summer releases. During off-season months, mu-

Table 5. Objective Function Values for Different Scenarios (dollars)

Scenario	Gross benefits	Direct costs	Salinity damage	Net benefits
Scenario 1[a]				
Agriculture	17,759,749	3,859,749	1,168,510	12,731,490
Municipal	638,185,409	135,850,861	13,900,466	488,434,082
Total	655,945,158	139,710,610	15,068,976	501,165,572
Scenario 2[b]				
Agriculture	14,959,749	3,859,749	1,114,064	9,985,936
Municipal	690,681,416	125,851,364	13,745,344	551,084,708
Total	705,641,165	129,711,114	14,859,408	561,070,644
Scenario 3[c]				
Agriculture	15,851,706	4,151,706	612,303	11,087,697
Municipal	703,626,364	117,726,364	12,234,377	573,665,623
Total	719,478,071	121,878,071	12,846,680	584,753,320

[a] No trade and no winter release

[b] Intrastate trade but no winter release

[c] Interstate trade and winter release

nicipalities must use groundwater resources (it is also possible to inject surface water into groundwater for storage, but at considerable costs). Seasonally, water flows and TDS levels do not significantly change from historical conditions because the diversion point for El Paso municipal water coincides with the diversion points of EPCWID. However, trade allows El Paso to obtain additional surface water from agriculture rather than expensive imports. As a result, net benefits increase in the model to $561 million, an increase of $60 million relative to scenario 1.

Unrestricted Trade

This scenario allows New Mexico and Texas municipalities to purchase consumptive use water rights from any irrigation district to facilitate growth in water demand. The institutions that would facilitate such trade do not exist, so it must be understood that the analysis is concerned with potential benefits that will result from the reallocation approximate to a free-trade system. The cost of implementing a trade system is not analyzed here. The net objective function value obtained for this solution is $584 million. The optimal seasonal releases are obtained as 104,000 acre-ft, 196,000 acre-ft, 260,000 acre-ft, and 162,000 acre-ft for the first, second, third, and fourth seasons, respectively. By 2040, El Paso has completely purchased all water rights to EPCWID No. 1. To even out supply, El Paso requests that its share of water be partially released during winter months. The effect is a significant increase in winter and fall instream flows (Fig. 6). Another factor is that El Paso purchases water rights from New Mexico farmers. As acreage in New Mexico is taken out of production and there is less diversion and return flow. Furthermore, there is more channel water to dilute return flow salinity. The net effect is a significant decline in TDS during all seasons (Fig. 7).

The increased instream flows counteract the return flow salinity and lower TDS levels below the EPA recommended standard level. Assuming a sustained 2% growth rate, El Paso needs to obtain 87% of its water supply from surface sources by 2043, diverting 400,000 acre-ft and Las Cruces diverting 100,000 acre-ft of water. The results are relatively insensitive to the assumption concerning urban demand elasticity because surface water is available from agricultural uses at a relatively low cost; whereas, demand for water by the urban sector is very inelastic. Agricultural acreage goes down from 121,000 to 60,000 acres. Table 6 indicates the decreases in agricultural acreage in the two districts, diversion of water, return flow, and groundwater pumping. Also indicated is the local marginal price (LMP) calculated at two major diversion dams (Mesilla diverts for EBID and American Dam diverts for Juarez, EPCWID, and the city of El Paso). The time pattern for LMP is predictable, reflecting the marginal values of water in agriculture adjusted for conveyance losses. Note that the value of water does not change during the time frame, indicating a basic result: surface water is not increasing in scarcity during this period. Total net economic return to water from reallocation increases by 16% to $83 million. Note that agricultural users will not be worse off because, as the holder of water rights, they may either sell or

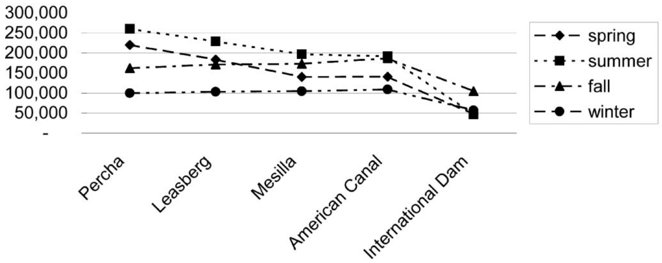

Fig. 6. Unrestricted trade: Seasonal water flow in Rio Grande (acre-ft)

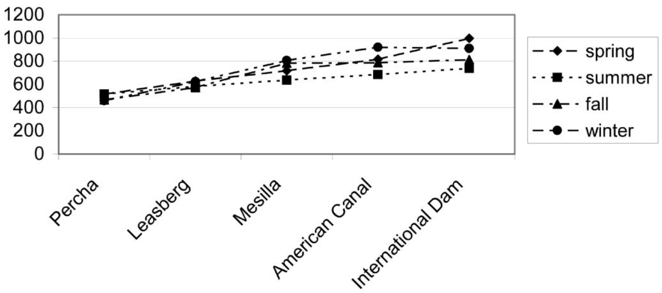

Fig. 7. Unrestricted trade: TDS levels by season in the Rio Grande Project (ppm)

Table 6. Agricultural Production, Water Use, and Local Marginal Prices

District	Year	Acreage	Farm delivery (acre-ft)	Conveyance loss (acre-ft)	Total supply (acre-ft) Surface water	Total supply (acre-ft) Groundwater	Return flow (acre-ft)	LMP[a]
EBID	2000	77,000	232,540	190,260	422,800	107,800	341,404	$35
	2003	77,000	232,540	190,260	422,800	107,800	341,404	$35
	2013	77,000	232,540	190,260	422,800	107,800	341,404	$35
	2023	77,000	232,540	190,260	422,800	107,800	341,404	$35
	2033	74,880	224,640	183,796	408,436	104,832	330,153	$35
	2043	60,192	180,576	147,744	328,320	84,269	265,392	$35
EPCWID	2000	44,000	132,000	132,000	264,000	0	184,800	$24
	2003	39,338	118,014	118,014	236,028	0	165,220	$24
	2013	26,938	80,814	80,814	161,628	0	113,140	$24
	2023	13,679	41,037	41,037	82,074	0	57,452	$24
	2033	0	0	0	0	0	0	$39
	2043	0	0	0	0	0	0	$39

[a] LMP is calculated at the Mesilla diversion dam for EBID and at the American diversion dam for EPCWID.

lease water to the municipalities. The model reflects this change in use but does not input a value to water rights. If the net benefit from agricultural water use and water rights sales is totaled, net benefit to this sector increases significantly.

Finally, the sensitivity analysis to total annual reservoir release indicates three important ranges: a higher marginal increase of benefit when city demands are the dominant factors, followed by irrigation demands, and finally, a small marginal increase caused by improved salinity levels in the river because of larger releases, i.e., dilution effect. By using a 50% release of water from the reservoir compared to a typical release, there would be no agricultural production by 2023; available water would be completely allocated to urban demands. The consequence of water shortage also results in rapidly increasing LMP by 2023. The LMP at the Mesilla Dam increases to $243 per acre-ft in 2023 for a 50% release, reflecting the opportunity cost of obtaining external sources of water for El Paso.

Conclusions

Although salinity is a problem in the Rio Grande as the water is progressively converted from agricultural to urban use, a low-cost solution is to allow all current water users in the project the ability to trade or lease their water rights. As municipalities require additional water, these entities can purchase the water through market exchange. It is in El Paso's interest to purchase a portion of its water upstream from EBID water-right holders. It is preferable not to divert this water into agricultural conveyance systems but allow it to flow in the main river channel thus reducing the effects of high salinity return flows. Given a small change in EBID's operating procedures, winter and fall salinity levels can be reduced from their current levels in excess of 1,200 ppm to less than 800 ppm, well within EPA recommended TDS level. In conclusion, the implementation of project wide market exchange of water rights results in a net benefit to the region, as opposed to high cost engineering alternatives.

The model developed here is a model of reallocation that simulates water allocation under unrestricted trade. We note that there are enormous obstacles to an interstate water market. The model only suggests there would be large benefits to the development of such a market.

Notation

The following symbols are used in this paper:

A,B,C,a,b = constants;
$A1$ = agricultural activity 1;
C_{b_i},C_{w_i} = quality parameter in Q_{b_i}, Q_{d_i} or $Q_{us_{(i+1)}}$, respectively;
$C_{d_{ij}},C_{p_{ij}}$ = quality parameter in $Q_{d_{ij}}$, $Q_{p_{ij}}$, respectively;
C_{ds_i},C_{us_i} = quality parameter in Q_{ds_i}, Q_{us_i}, respectively;
C_{ppt_i} = quality parameter in Q_{ppt_i}
$C_{r_{kji}}$ = quality parameter in $Q_{r_{kji}}$;
$C_{w_{ij}}$ = weighted quality parameter at demand point j in reach i;
$C(K_{p_{ij}}Q_{p_{ij}})$ = cost of pumping at demand point j in reach i;
$C(Q)$ = TDS concentration in Q;
$C(Q_{d_{ij}},Q_{p_{ij}})$ = cost of surface water and groundwater supplies;
$D(C_{d_{ij}},C_{p_{ij}})$, $D(C_{w_{ij}})$ = damage due to poor quality surface water and groundwater supplies;
$K_{d_{ij}},K_{l_{ij}},K_{p_{ij}},K_{s_{ij}}$ = coefficient of flow for $Q_{d_{ij}}$, $Q_{l_{ij}}$, $Q_{p_{ij}}$, $Q_{s_{ij}}$, respectively;
$K_{s_{kji}}$ = coefficient of flow for $Q_{s_{kji}}$
K_{b_i},K_{s_i} = coefficient of flow for Q_{b_i}, Q_{s_i}, respectively;
K_{ppt_i} = coefficient of flow for Q_{ppt_i};
N = Number of households in city/town;
$P(Q_{d_{ij}},Q_{p_{ij}})$ = profit as a function of allocated surface water and groundwater supplies;
Q = yearly water supply in acre-ft;
Q_{b_i} = In-stream transfer to reach i;
$Q_{d_{ij}}$ = diverted flow from reach i for demand point j;
Q_{ds_i} = Flow at the downstream end of reach i;
$Q_{l_{ij}}$ = Consumptive use in reach i at demand point j;
$Q_{lm(zij)}$ = Return flow from reach i that was diverted for purpose j to l reaches downstream from the water diverted during season m and returning during season z;

$Q_{p_{ij}}$ = pumped flow from reach i for demand point j;
Q_{ppt_i} = flow into reach i accountable to net precipitation contribution;
$Q_{r_{kji}}$ = return flow from demand point j in reach k to reach i $(k \neq i)$;
Q_{s_i} = In-stream seepage loss in the stream in reach i;
$Q_{s_{ij}}$ = Seepage loss in reach i on the way to demand point j;
$Q_{s_{kji}}$ = Seepage loss in the return flow from demand point j in reach k to reach i $(k \neq i)$;
Q_{us_i} = flow at the upstream end of reach i
R = Return (dollars/year);
$R1$ = reach 1;
S_z = season z;
Z = net profit (objective function);
z = season;
α, β = crop specific constants.

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