Water Supply Analysis for Restoring the Colorado River Delta, Mexico

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Abstract: This paper employs an economic-engineering optimization model to explore water supply options for environmental restoration of the Colorado River Delta, Mexico. Potential water sources include reductions in local agricultural and urban water use through water markets, wastewater reuse, and additional Colorado River flows from the United States. For these alternatives, the optimization model estimates operating and water scarcity costs, water scarcity volumes, and marginal economic costs of environmental flows and values of additional Colorado River flows from the United States over a range of required delta environmental flows. Economic values for agricultural and urban water uses were estimated by two ancillary models. The results provide insights into economically promising water supplies for restoration activities. Quantifying the trade-off between agricultural and urban economic valuation and environmental flows provides a framework for decision makers to quantify their valuation of environmental flows. The model also provides a framework for integrating additional knowledge of the system as information becomes available.

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Introduction

Providing water for environmental purposes is a difficult issue in many parts of the world. Urban and agricultural users often have first priority in water allocation, for legal and economic reasons. A vast effort has been made to economically value environmental water uses, including revealed preference, expressed preference, value transfer, and meta-analysis approaches (Young 2005).

This research explores economical sources of water for environmental restoration within the framework of an economic-engineering optimization model driven by minimizing water scarcity costs for urban and agricultural uses, within infrastructure, hydrologic, regulatory, and environmental constraints. The marginal economic costs of environmental water use are given by the shadow values on minimum environmental flow constraint. Economic scarcity costs for modeled urban and agricultural water users are obtained from water demand curves. The Colorado River Delta of Mexico (CRD), surrounded by a major agricultural region and fast-growing border cities, is used as the study case. Policy alternatives for restoration of the delta include various mandated minimum flows, wastewater reuse, and water purchases or transfers from local agriculture and outside the region. Valuation of environmental flows is implied when decision makers select their preferred trade-off between environmental flows and economic costs to other water users.

This paper first briefly reviews environmental flow valuation techniques. Second, models are proposed to economically value agricultural and urban water uses and integrate this knowledge with local hydrologic, infrastructure, and management constraints. An application to the Colorado River Delta in the Mexicali Valley, Mexico, is then presented. Results and conclusions from the application follow.

Valuing Water for Environmental Purposes

Literature on valuing water for environmental uses is developed mostly for recreation, aesthetic, and existence value (Loomis 1998). Existence value describes the utility individuals derive from knowing a resource exists. Direct market data on willingness to pay or prices for environmental uses is very rare, so alternative valuation techniques have been developed. Young (2005) identifies broad techniques for valuation of water as an environmental public good: revealed preference, expressed preference, benefit transfer, and meta-analysis. The first two are the most common in the literature.

Revealed preference techniques, such as the travel cost method, indirectly estimate value using observed data from actual environmentally related decisions made by consumers. Expressed (stated) preference methods (e.g., contingent valuation) estimate the value of environmental water by questioning individuals about their valuation under different scenarios. Benefit transfer is less common, but suitable when extensive field research is unavailable. Benefit transfer valuation methods adapt results from previous studies to a different location and conditions. In meta-analysis, statistical analysis of previous research estimates are used to provide initial information for benefit transfer (Young 2005).

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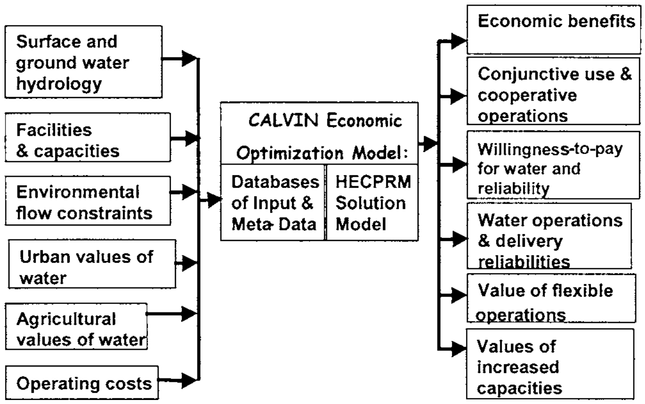

Fig. 1. Data flow schematic in CALVIN (Draper et al. 2003, ASCE)

This research uses system model results to establish a framework for revealed preference estimates of the economic value of environmental flows. Agricultural, environmental, and urban water uses exist within a complex hydraulic network. First water is economically valued for agricultural and urban uses by applying common valuation techniques. Total economic costs for the system are the sum of scarcity costs for these uses plus operating costs (pumping, treatment, etc.) for the region. Water is assumed to be a scarce resource for the three users.

The opportunity cost of dedicating water to environmental uses rather than deliveries for the other two uses is then the value of the shadow costs on the environmental flow constraints in the system model. Valuation of environmental flows is then implied by decision-maker selection of a point of operation on the tradeoff curve between environmental flows and other economic performance. As such, this approach differs from mainstream contingent valuation and travel cost method techniques. Shabman and Stephenson (2000) review shortcomings of the aforementioned methods.

For this study, willingness to pay for environmental water is a by-product of a larger, user-interrelated water resources study. One advantage of this approach is that associated opportunity costs of alternative uses of water and operation costs are explicitly considered. Although water quantity or minimum environmental instream flows (MIFs) are common attributes, water quality also is important for agriculture and the CRD. However, the scope of this research does not extend to water quality issues. Water quality considerations would not shift the model results greatly since there is an upper bound for Colorado River salinity from Treaty Minute 272 of 1973.

Model

The economic-engineering optimization in this study uses the CALVIN model (Jenkins et al. 2001, 2004), which is built around the HEC-PRM optimization model (USACE 1994). CALVIN was developed and successfully applied for strategic water management in California. The model optimizes and integrates water operations and allocation based on costs and economic water scarcity for urban and agricultural users (Fig. 1). The CALVIN model has provided promising insights for water management regarding water markets, facility expansion, dam removal, conjunctive use, economic costs of environmental restrictions, and users' economic willingness to pay for water (Jenkins et al. 2004; Lund et al. 2003; Medellín-Azuara and Lund 2006; Null and Lund 2006; Pulido-Velázquez et al. 2004). Most recent applications of CALVIN include adaptations to climate change for the state of California (Medellín-Azuara et al. 2006; Tanaka et al. 2006).

CALVIN belongs to the category of generalized network flow optimization models (Labadie 2004), which can account for flow losses and gains. To minimize total operation and scarcity cost in a region, HEC-PRM solves the set of equations below (Jenkins et al. 2001)

$$\text{Min}_{x\geq 0} Z = \sum_m \sum_n c_{mn} X_{mn} \tag{1}$$

$$\sum_m X_{nm} = \sum_m a_{mn} X_{mn} + b_{n,} \; \forall \; n \tag{2}$$

$$X_{mn} \leq u_{mn} \quad \forall \; m,n \tag{3}$$

$$X_{mn} \geq l_{mn} \quad \forall \; m,n \tag{4}$$

where Z=total cost of flows throughout the network; X_{mn}=flow leaving node m towards node n; c_{mn}=economic cost; b_n=external inflows to node n; a_{mn}=gain/loss on flows in arc mn; u_{mn}=upper bound on arc mn; and l_{mn}=lower bound on arc mn (Jenkins et al. 2001). Economic costs are assigned to water scarcity for each agricultural and urban demand location. Each demand location has a water delivery target and piecewise linear costs for deliveries less than its target.

Both operating costs and economic cost of water scarcity for water users are required. Water scarcity costs are represented by convex penalty functions developed from piecewise linear integration of a marginal willingness-to-pay curve for water for each agricultural and urban water user.

Agricultural Demand Model

Economic values for agricultural water deliveries were estimated by an inductive valuation technique known as positive mathematical programming or PMP (Howitt 1995), extending an earlier U.S.-California application of the Statewide Agricultural Production Model (SWAP) by Howitt et al. (2003). Farmers in an area are assumed to make crop and water use decisions to maximize profits within water and land constraints. SWAP calibrates to historically observed values of crop, water, and land use and output. Willingness to pay for water is obtained by increasingly restricting water availability to farmers and observing the shadow values of water use.

A multiregion and multicrop agricultural production model was developed for this study following Howitt (2006). Technology is represented by a constant elasticity of substitution (CES) production function, which restricts substitution effects among production factors. Constant intertemporal yields are assumed, but spatial variation of yields is allowed to represent heterogeneity in land quality.

Details of the current PMP model appear in Medellín-Azuara (2006). The first step in PMP is to obtain marginal values on model calibration constraints. In a second step, marginal values from the previous step are used to calculate parameters needed by a quadratic total cost function and the CES production function. The last step in PMP is to solve a nonlinear constrained profit maximization program as follows:

$$\text{Max}_{x\geq 0}\prod = \sum_g \sum_i v_{gi}Y_{gi} - \sum_g \sum_i \sum_j (\alpha_{ig}x_{gi,\text{land}} - \gamma_{ig}x^2_{gi,\text{land}}) \tag{5}$$

$$Y_{gi} = \tau_{gi}\Big[\sum\nolimits_j \beta_{gij}x_{gij}^{-\rho}\Big]^{-\upsilon/\rho} \tag{6}$$

$$\sum_i a_{gij}x_{gij} \leq b_{gj} \quad \forall\, g,j \tag{7}$$

$$xm_{gm} \leq \sum_i \text{met}_{gim}x_{gi,\text{water}} \quad \forall\, g,m \tag{8}$$

$$\sum_m xm_{g,m} \leq \text{availwater} \cdot b_{gj} \quad \forall\, g \text{ and } j = \text{water} \tag{9}$$

In Eq. (5), Y_{gi} and ν_{gi} represent respectively physical output [as a CES production function of Eq. (6)] and unit price of crop i in area g. The scale (yield) parameter of the CES production function in Eq. (6) is referred as τ_{gi}, whereas the share parameters of the production function for each crop are represented by β_{gij}. The variable x_{gij} denotes usage of factor j in production of crop i of region g. Production factors j include labor, land, water, and an aggregate of supplies such as fertilizer and pesticides. These factors were indexed by land in crop i. The second term in Eq. (5) contains a quadratic PMP cost function with parameters α and γ (Howitt 2006). Eqs. (7) through (9) are constraint sets for production factors, monthly water use($xm_{g,m}$) and available water $b_{g\text{water}}$ for each region. The variable met_{gim} is the observed fraction of the total annual water use $x_{gi,\text{water}}$ for crop i in area g.

A derived water demand curve for each area is obtained by incrementally reducing the parameter availwater in Eq. (9) above from 1.0 to 0.6. The program of Eqs. (5) through (9) was coded to run in GAMS (Brooke et al. 1998). The output of the program provides shadow values of water from 60 to 100% water availability, which is used to derive water scarcity penalty functions used in CALVIN (Fig. 1).

Urban Demand Model

An econometric model was used to estimate the residential price-elasticity of water demand. This model is a hybrid of Billings and Agthe (1980) and Nieswiadomy and Molina (1989), which includes the quantity demanded (per user), the marginal price, a difference variable, income and seasonal variables, and instrumental variables to overcome simultaneity issues. The difference variable was introduced by Taylor (1975) and refined by Nordin (1976) to overcome the alleged inherent endogeneity in demand models under block rate schedules. This explanatory variable is defined as the difference between the water bill and what would be paid if all consumption were charged at the marginal price.

In this model, water used per metered connection is a proxy for household consumption in time. Water used by the average household (Q_t) in time t is assumed to be a function of the price in the last block rate (marginal price, P_t), Nordin's difference variable D_t (Schefter and David 1985), income Y_t, a seasonal dummy variable $\boldsymbol{W_t}$, average monthly reference evapotranspiration ET_t, and monthly precipitation R_t. The regression equation is

$$Q_t = \beta_o + \beta_1 P_t + \beta_2 D_t + \beta_3 Y_t + \beta_4 ET_t + \beta_5 R_t + \delta \boldsymbol{W_t} + u_t \tag{10}$$

where u_t=error term and $\boldsymbol{W_t}$=vector of dummy variables for three out of four quarters in the year. Marginal price P_t and difference variable D_t are instrumented variables in a first-step regression (Nieswiadomy and Molina 1989). Instruments for marginal price and difference variables are the block rate identification (1–12), the fiscal year, and a seasonal variable for the month at time t.

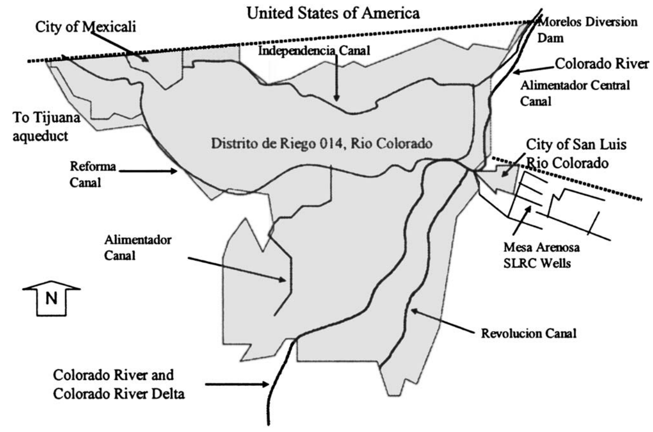

Fig. 2. Location of cities of Mexicali, San Luis Río Colorado, Irrigation District 014 and major canals

In this study, nonresidential uses including commerce, government, and industry are assumed to be fixed. This assumption is less realistic for commercial uses and more realistic for industrial and governmental uses. The contribution of water to industrial end products is minor compared to capital and other production inputs (Young 2005).

Case Study and Policy Alternatives

The Mexican portion of the Lower Colorado River Delta (CRD) occupies more than 180,000 ha, which is only 10% of the delta's area before upstream water development began beginning in the early 1900s in the United States and Mexico (Glenn et al. 2001). The Colorado River (Fig. 2) is the main water source for northern Baja California, whose rainfall averages roughly 200 mm/year. The CRD is the breeding ground for thousands of migratory birds as part of the Pacific Flyway and home of endangered species, including the Yuma clapper rail and the desert pup fish (Anderson et al. 2003).

Since the 1930s, upstream diversions for agricultural and urban uses have greatly reduced and altered the pattern of delta flows, causing severe habitat loss and deterioration of water quality and abetting invasions of exotic species (Glenn et al. 2001). Migratory birds have suffered reduced wetland and wintering habitat (Zengel et al. 1995). Endangered species such as the Yuma clapper rail rely on cattail habitat for breeding. The bird populations are prone to collapse because low flow regimes affect cattail coverage (Hinojosa-Huerta et al. 2001). Most of the remaining CRD has been protected since 1993 by the Mexican Environment Ministry (SEMARNAT) as part of the Biosphere Reserve of the Gulf of California. Nevertheless, severe droughts, increasing agricultural and urban demands, and institutional constraints are challenges for CRD restoration.

In 1944 Mexico and the United States signed a water treaty that guaranteed Mexico 1,850 million cubic meters of water per year (MCM/year) from the Colorado River. Other issues were to be addressed through the newly created International Boundary and Water Commission (IBWC). The initial water treaty did not address population growth or water quality. In the early 1960s, as a result of drainage water from Arizona diversions, salinity exceeded the historical 1,000 ppm level (Garcıa-Acevedo 2000). After long rounds of negotiation, in 1973 Minute 242 was signed to amend the water treaty. The U.S. section of the IBWC agreed to deliver water to Mexico with a salinity level less than 130 ppm (±30 ppm) above the salinity observed at the U.S. Imperial Dam. Minute 306 of 2000 sets the framework for binational studies and recommendations concerning water resources management in the CRD.

Salinity and flow regimes determine vegetation coverage in the CRD (Zengel et al. 1995). However, Clinton et al. (2001) and others [e.g., Zamora-Arroyo et al. (2001)] argue that the main cause of CRD environmental problems is low inflow. Even when water exceeding the 1,850 MCM quota reaches the Mexican border, this water has been assigned to agricultural use or aquifer recharge (Clinton et al. 2001). Another cause of the low flows to the CRD is increasing population in northern Baja California. Salinity has increased from drainage flows from upstream diversions (Cohen and Henges-Jeck 2001).

Once invasive species are established, native vegetation cannot recover. Stromberg (2001) discusses the causal relationship between flow regimes and ecosystem functions in the CRD. Several studies indicate that the riparian corridor of the CRD requires annual flows of about 40 MCM, with pulse flows of 320 MCM every 4 years (Luecke et al. 1999; Pitt et al. 2000). Studies in the region seem to agree on the amount of water needed for restoration and maintenance of the CRD habitat (including the Rio Hardy, the Cienega de Santa Clara, the riparian corridor in the U.S.–Mexico limitrophe, and south towards the Gulf of California). However, the costs and regional management of dedicated flows are largely unexplored.

Agriculture and Irrigation Water in Mexicali Valley

Irrigation District 014 is located south of the northern U.S.–Mexico border of the Mexican states of Baja California and Sonora (Fig. 2), known as the Mexicali Valley. Of its gross area of 350,000 ha, 250,000 ha can access irrigation systems. About 208,000 ha (roughly 84%) have water rights for irrigation. Of these, 26,647 ha are located in the municipality of San Luis Rio Colorado, Sonora (SLRC), and the rest in Mexicali, Baja California. Being among the most productive regions in Mexico, the predominantly commercial agriculture in the Mexicali Valley yielded nearly U.S. $280 million in 2004 (SAGARPA 2006).

The main crops in the Mexicali Valley are alfalfa, cotton, and wheat, together representing 77% of the planted area and 54% of all agricultural value (SAGARPA 2006). High-value crops such as asparagus and green onion add 25% more to the total agricultural value. This study used the crop mix from the Mexicali Valley detailed in Table 1. Alfalfa, cotton and wheat currently use about 83% of all water deliveries.

While water might be scarce for agriculture in this region, the Mexicali Valley is unique in Mexico since it has a very firm lower bound for water availability. The 1944 U.S.–Mexico Water Treaty stipulates to Mexico at least 1,850 million cubic meters (MCM) per year, except for an extraordinary drought, which is loosely defined in the treaty (Cohen 2006). The United States can provide highly reliable water deliveries to Mexico because of very sizable reservoir capacity on the Colorado River in the United States. Thus there is little interannual hydrological variability in Colorado River water availability to Mexico.

The Mexicali aquifer is another source of water, including the Mesa Arenosa, a small well bank near SLRC. The Mexicali aquifer is the largest aquifer in the country, with an annual availability of 700 MCM, recharged mostly from agricultural leakage, drainage water, and infiltration from the Colorado River and the Mesa Arenosa. Around 725 wells in the Mexicali Valley and Mesa Arenosa yield 700 MCM/year. Nearly 197 MCM/year in the Mesa Arenosa are allocated for urban use in the northern border cities of SLRC, Mexicali, Tijuana, Rosarito, and Tecate. About 82% of the 197 MCM annual quota goes to the large cities of Mexicali via de Independencia Canal and to Tijuana, through the Reforma canal, and then through the Colorado River–Tijuana aqueduct.

Table 1. Crop Mix for Agricultural Demand Model Using Data from CNA (2006a)

Crop name	Cultivated land (ha)	Average yields (ton/ha)	Water delivered (000 s/m^3)
Alfalfa	28,426	75.5	436,785
Asparagus	2,039	4.95	38,645
Canola	3,403	3.4	15,180
Cotton	21,917	3.6	266,126
Green onion	4,488	11.99	33,672
Rye grass	4,763	41.86	38,831
Sorghum grain	3,224	12.25	27,302
Wheat	85,775	5.04	792,167
Total	*154,035*		*1,648,708*

Urban Uses in Colorado River Delta

The two large urban centers in the Mexicali Valley are Mexicali and San Luis Rio Colorado. Mexicali is south of the Mexico–U.S. border of Baja California, with a 2005 population of 855,962, a population growth rate of 2.0%, and 218,912 households (INEGI 2005). The city is surrounded by Irrigation District 014. Average household income in Mexicali is about 15% higher than the national average (INEGI 2000, 2002, 2004). For Mexicali, water is provided by the Comisión Estatal de Servicios Públicos de Mexicali (CESPM), supplying 84% of the municipality and 98% of the city, with 245,214 residential customers in 2005 (CESPM 2006) (For use see Table 2).

San Luis Río Colorado is on the northwest Mexico–U.S. border of the Mexican state of Sonora. Its population is 157,076 with 39,997 households (INEGI 2005). The city was founded late in the 19th century as agriculture flourished in the Mexicali Valley. Information on per capita or household income for San Luis Río Colorado was unavailable. In San Luis Río Colorado, the public water utility is the Organismo Operador Municipal de Agua Potable, Alcantarillado y Saneamiento de San Luis Río Colorado (OOMAPAS). Of 55,830 customers, 53,084 were residential in

Table 2. Average (2002–2005) Urban Water Use in Colorado River Delta

	Mexicali		San Luis Río Colorado	
Use cases	Consumption (1,000 m^3/year)	Share (%)	Consumption (1,000 m^3/year)	Share (%)
Residential	57,125	73.3	26,765	88.8
Commercial	7,197	9.2	1,740	5.8
Industrial	6,352	8.2	1,629	5.4
Other	7,234	9.3	26,765	N/A
Total	*77,908*	*100.0*	*1,740*	*100.0*

Sources: CESPM (2006), OOMAPAS (2006).

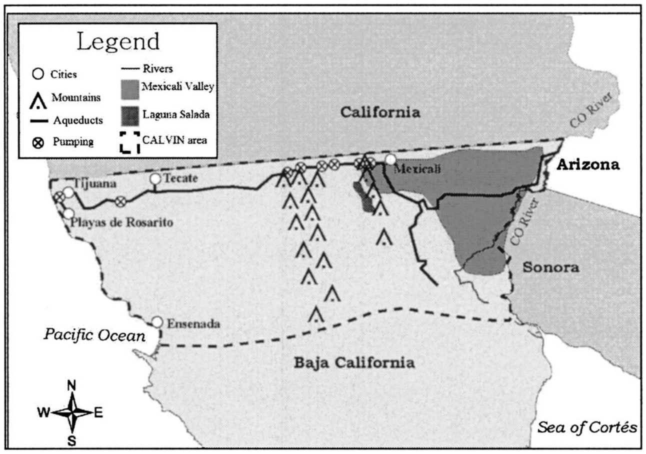

Fig. 3. Coverage of CALVIN Region 6, Baja California (adapted from Malinowski 2004)

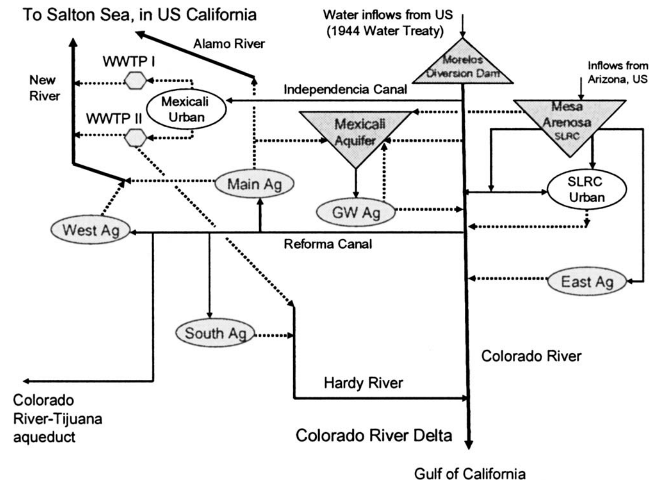

Fig. 4. Simplified schematic of CALVIN Region 6 at Colorado River Delta and Mexicali Valley—WWTP refers to wastewater treatment plants in Mexicali

2005. Nearly 2,000 new residential customers ($\sim 4\%$) have been added every year in the last 6 years (OOMAPAS 2006). Water in urban centers is mostly for residential use (Table 1). For Mexicali and San Luis Rio Colorado, yearly average residential use (2002–2005) represents roughly 73 and 89%, respectively, of the total use shown in Table 2.

Application of CALVIN

Consistent with the research objectives of this study, Region 6 (Baja California) of CALVIN, was developed to estimate the economic cost for agricultural and urban water users of various levels of CRD restoration flows. Regions 1–5 are in U.S.–California. Water demand levels for agriculture and cities are projected for the year 2020. The marginal economic costs of environmental flows for the CRD are given by the shadow value of the minimum flows constraint for the CRD [i.e., Eq. (4)].

Fig. 3 depicts CALVIN Region 6, Baja California. Urban demands include the cities of Ensenada, Mexicali, Rosarito, SLRC, Tecate, and Tijuana. Agricultural water uses include the valleys of Guadalupe, Maneadero, and Mexicali. For this study, the eastern side of Region 6 (Mexicali Valley) was used. Demand sites in this subregion include the cities of Mexicali and SLRC and four agricultural locations within the Mexicali Valley. Hydraulic infrastructure in the model includes major canals, wastewater treatment facilities for Mexicali, and the Colorado River–Tijuana aqueduct.

Fig. 4 shows a simplified network representation of the CRD portion of CALVIN Region 6. Water supplies for the region are the Colorado River and the Mexicali aquifer. Data on Colorado River inflows crossing the Mexico-U.S. border are from the National Water Commission. (Comisión Nacional del Agua or CNA) (CNA 2006a), as are estimates of groundwater usage and recharge for the Mexicali aquifer. Given the regularity of the predominant water source (the Colorado River), the model runs are quasi-steady state, for 5 years with little over-year operation of storage.

Policy Alternatives and Modeling Sets

Modeling sets of this study include year 2020 projected consumption in the urban centers and agriculture. The Rio Colorado–Tijuana aqueduct is assumed to have increased capacity to $5.2\ m^3/s$ and is operated at this full capacity (164 MCM/year) to supply growing urban demands in the Tijuana metropolitan area. Mexicali and SLRC use becomes roughly 100 and 42 MCM/year, respectively. Minimum water flows for the CRD follow current recommendations of 40 MCM/year minimum constant flow and pulse flows of 320 MCM every 4 years, averaging 10 MCM per month.

Policy alternatives include mandated minimum flows, treated wastewater reuse, and water markets and transfers. For all policy alternatives, minimum environmental flow constraints for the CRD are varied from 0 to 20 MCM/month to obtain shadow values of water for environmental flows at each flow level. For the first alternative, the system can supply environmental flows by operational changes to the Mexicali Valley network and purchasing water from agricultural and urban users in the Mexicali Valley. The Mexicali Valley already has an active internal water market.

The second alternative adds treated wastewater costing $200/TCM to the options available in the first alternative. For this cost it is assumed that treated wastewater is sold at the lowest possible fee published (Estado de Baja California 2004). Wastewater reuse is limited to about 50% capacity of the future Las Arenitas wastewater treatment plant in Mexicali (15.8 MCM/year) (EPA 2006), with capacity cost being omitted from the model.

Finally, the third alternative allows water to be purchased from elsewhere (presumably the United States) at an assumed-to-be inexpensive rate of $30/TCM, in addition to the options available in the first and second alternatives. While this price is much less than water market transfers between the Imperial Valley Irrigation District and the City of San Diego, this price does justify low-value water uses in Imperial, Palo Verde, and the Central Arizona project.

Data and Economic Value of Agricultural and Urban Water

CALVIN uses data on infrastructure capacities, major conveyance facilities, aquifers, reservoirs, and economic water demands. Water shadow values for agricultural and urban uses arise from their respective water demand models. Information on facilities is mainly from CNA and the state utilities CESPM and OOMAPAS.

Table 3. Agricultural Water Shadow Value in Mexicali Valley

Water availability (%)	Shadow value (US$/000 s/m^3)			
	East	Main	West	Groundwater
100	25	37	21	17
90	30	41	25	23
80	35	46	31	31
70	41	50	38	39
60	47	53	44	50

Hydrology includes water deliveries from the United States through the Colorado River and from groundwater recharge. CNA provided data on Colorado River water deliveries to Mexico (CNA 2006b). For groundwater, CNA (2004) and the former Water Resources Secretariat (SRH 1972) estimate an annual recharge of 700 MCM/year for the Mexicali aquifer. Of these, 100 MCM/year is stream recharge from the Colorado River, 100 MCM/year is lateral inflow from the Mesa Arenosa aquifer, and 500 MCM/year is percolation of Mexicali Valley irrigation water.

For the agricultural demand model, CNA's irrigation district records cover 60 months of water deliveries and cultivated land per crop for each irrigation subdistrict or module. Production costs and factor usage other than land and water were obtained using statistical information from the Agriculture Ministry (SAGARPA) and from work in progress by the Veterinary Institute of the University of Baja California in Mexicali. Finally, the 22 modules were consolidated into four major areas, considering geographical location, water sources, and land quality attributes. These four areas are: (1) the main Mexicali Valley; (2) mostly groundwater-irrigated agriculture; (3) eastside agriculture; and (4) westside agriculture. Irrigation water demand curves for each irrigation area were found by systematically limiting water availability from 100% down to 60% of current use in 10% steps, as shown in Table 3 and Fig. 5.

Overall, agriculture in the west of the Mexicali Valley has the lowest marginal value for irrigation water when availability drops below 80%. The main valley has the highest value, whereas the east side has a shadow value near the average of the four regions.

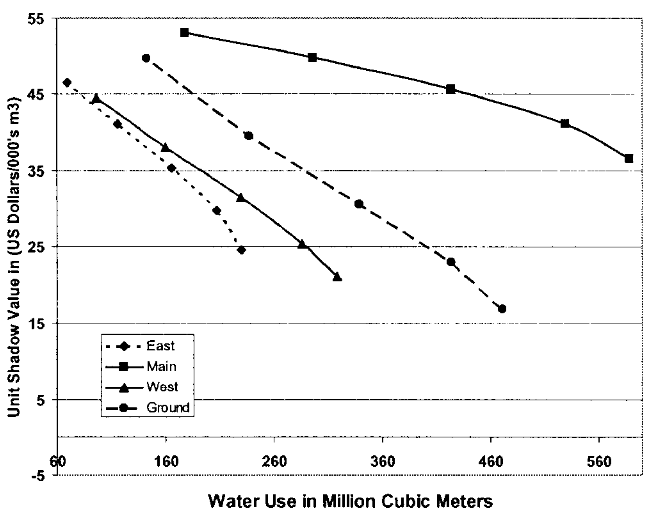

Fig. 5. Shadow value for agricultural water uses in Mexicali Valley

The groundwater area follows a steepest pattern, as seen in Fig. 5, beginning as the lowest water value at full availability and passing valuation in other two regions at the lowest level of availability. These shadow values of water for agriculture were converted into penalty functions following Jenkins et al. (2001, 2003) and water use was scaled up to represent all agricultural use in the Mexicali Valley.

Data sources for residential use in Mexicali include water use reports of CESPM (2006) and INEGI's household income national surveys (INEGI 2000, 2002, 2004). Water consumption data from CESPM is monthly from January 2000 through December 2005. CESPM's database has water consumption disaggregated into 15 price blocks (Estado de Baja California 2004). The first block (up to 5 m^3/month) has a flat rate, followed by 14 blocks ranging from 5 to 10 m^3, with incrementally increasing unit prices. For each consumption block, the database provides total use, number of customers, and total revenue raised by the utility. Six years (2000–2005) of monthly observations per consumption block were included in the estimations. Currency in the analysis is set at 2002 pesos using the Mexican Central Bank's Consumer Price Index (Banco de México 2006).

Regression results are comparable to those found in the water demand literature for residential water demand studies in the United States and Europe. Price elasticity was within the range of most studies. Espey et al. (1997) conclude from their 24 studies that 90% of the price elasticity estimates fall between 0 and −0.75. For Mexicali, price elasticity at mean consumption's marginal price is −0.76. For the city of SLRC, estimated price elasticities were −0.62, explained in part by SLRC not having an increasing block rate schedule. Cities east of Mexicali are out of the scope of econometric estimation for the current study. Instead, Colorado River–Tijuana aqueduct deliveries were constrained at full capacity.

Model Results

Model runs for each policy alternative and level of minimum inflow requirements were performed by CALVIN. Results include the overall cost to the Mexicali Valley region, water scarcity quantities for urban and agricultural uses, the marginal cost to agricultural and urban users of environmental outflows (shadow values on these constraints), and the marginal economic value of additional inflows of Colorado River water from the United States. Initially, current recommended minimum water flows into the CRD were modeled as a lower bound constraint. For this set of modeling runs, outflows to the Colorado River Delta were set at 10 MCM per month.

Table 4 shows a summary of the status quo without mandated flows for the CRD versus the currently recommended minimum flows. Status quo considered urban growth in the cities of Mexicali, SLRC, Tijuana, and Tecate, but no major regional facility expansions. Future urban demands for year 2020 may affect agricultural demands, which face an average 66.2 MCM/year in scarcity, reducing agricultural production by close to $1.5 million dollars per year (second column of Table 4).

Interestingly, willingness to pay for additional water from the Colorado River north of the border is only $13.5/TCM. For water year 2004–2005, CNA's water price to farmers was about $7/TCM. Thus, this willingness to pay for water beyond the water treaty quota is almost double the current price to farmers. Scarcity is not uniform in the Mexicali Valley; agriculture in the west side of the valley is the most vulnerable to water shortages. The east

Table 4. Annual Water Scarcity, Scarcity Costs, and Opportunity Costs for Environmental Flows to CRD and US–Mexico Transboundary Flows

Values	Status quo (without environmental flows)	Mandated minimum average flows of 10 MCM/month		
		Water markets	Facilities and markets	Facilities, Markets, and U.S. flows
Annual water scarcity for agriculture (MCM/year)	66.2	158.4	144.3	121.2
Annual scarcity cost for Agriculture (K$/year)	1,460	3,830	3,406	2,819
Shadow value of environmental flows ($/TCM)	N/A	52.21	50.6	48.4
Shadow value transboundary flows ($/TCM)	13.52	23.5	22.85	21.78

Note: Currency is in U.S. dollars.

side and the main Mexicali Valley are not expected to experience scarcities due to higher marginal values for water use.

Scarcity and its cost would grow if the Mexican government mandates the current recommended minimum flows for the delta (column 3, Table 4). If no additional facilities are in place, water scarcity for agriculture can be as high as 158.4 MCM/year. This implicitly assumes water markets are active, with low transaction costs to shift the burden of increased environmental flows to the lowest valued uses. Low-value agriculture is expected to forfeit or sell water to other uses. The region already has an active internal water market. The shadow value of environmental flows averages $52.2/TCM. Willingness to pay for additional water from the United States increases with the mandated flows to $23.50/TCM.

When more water is available, even at a high cost, water scarcity and its cost may decrease. Reuse of 15.8 MCM/year from the wastewater treatment facility reduces water scarcity to 144.3 MCM/year. The shadow value of water for environmental flows drops slightly to $50.6/TCM. Willingness to pay for additional transboundary water imports remains low at $22.85/TCM on average, but building this water reuse capacity has substantial capital and operating costs, with water from this facility being proposed for sale at $200/TCM. At recommended minimum flows for the CRD, the net present value of the wastewater reuse facility's regional water supply benefits are $105.8 million ($5.29 million/year reduction in regional water costs discounted at 5%/year over an infinite lifespan).

Finally, if additional low-cost water is found, the opportunity costs of environmental water flows drops dramatically. Table 4 shows a model run in the last column where water can be bought in any amount at a rate of $30/TCM at the U.S. border. Even with such inexpensive additional water supply, water scarcity remains for agriculture in the Mexicali Valley (121.2 MCM/year), although average annual scarcity costs drop by almost a million dollars per year.

The same policy alternatives were analyzed over a wide range of minimum environmental flows. Fig. 6 shows the results of gradually increasing mandated water flows for the CRD from zero to 20 MCM/month (zero to 240 MCM/year). As expected from Table 4, mandated flows with and without wastewater reuse have similar shadow values for environmental flows to the delta. This could be explained in part by the relatively low volumes of treated wastewater.

For 2005, prices for wastewater range from $200 to 600/TCM (CESPM 2006), whereas agricultural water price was less than $10/TCM. For larger volumes of dedicated flow, additional low-cost water imports seem to be the best alternative to provide water to the delta, although the marginal economic value of transboundary water imports remains less than $40/TCM for all cases. Opportunity costs on environmental constraints flatten slightly after 10 MCM/month flows if low-cost water is available.

The total annual opportunity costs of delta environmental flows are depicted in Fig. 7. As expected from Fig. 6, inexpensive ($30/TCM) water imports become the most cost attractive when minimum flow requirements exceed 180 MCM/year. However, this price is much lower than the values of water in southern California estimated in other CALVIN studies, which can be as high as $80/TCM or as observed in recent long-term water

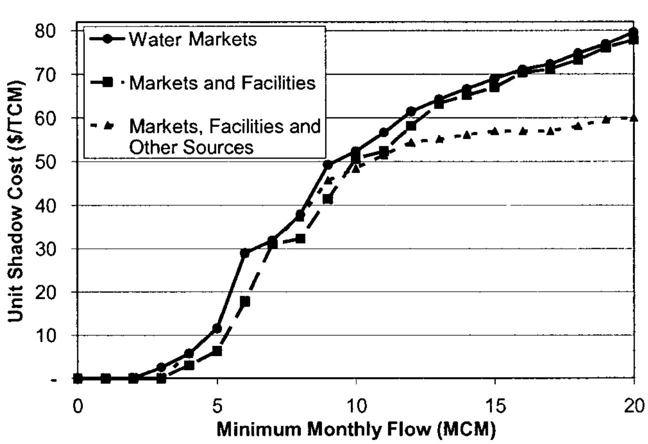

Fig. 6. Shadow value of minimum environmental flows in Colorado River delta

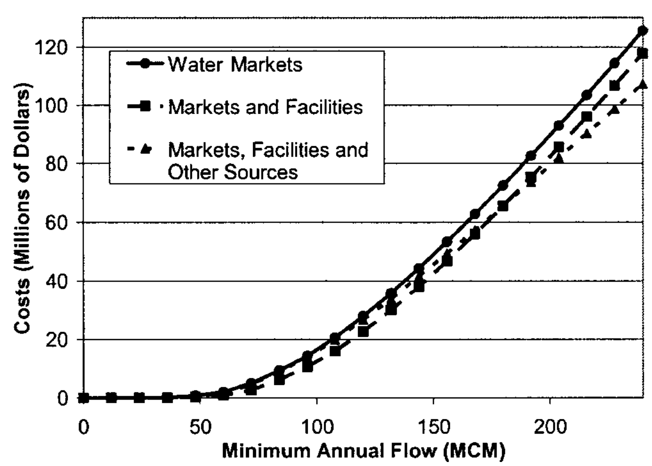

Fig. 7. Total annual opportunity cost of minimum flows in Colorado River delta

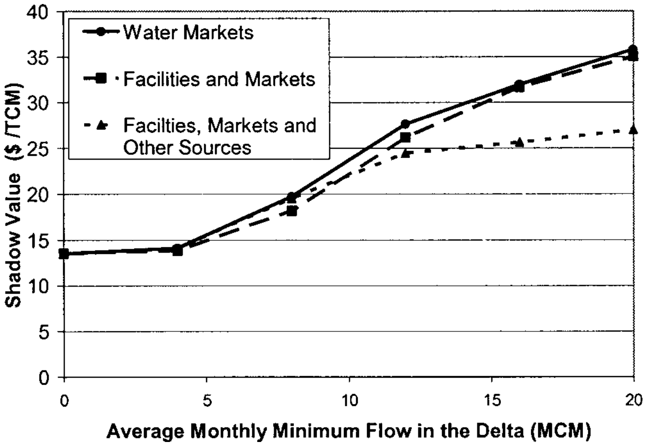

Fig. 8. Willingness to pay for additional transboundary water flows from the United States

markets in southern California (over $160/TCM). Opportunity costs in the Mexicali Valley for environmental flows rise to almost $70 /TCM if water import prices are raised to $60 (not shown).

Given the relatively high economic value of urban water uses in the Mexicali Valley, water scarcity only occurs for agriculture for all alternatives and levels of environmental flows. The cities west of the Mexicali Valley (such as Tijuana) also have fixed exports of water from the Mexicali Valley, through the Colorado–Tijuana aqueduct, which could be as high as 164 MCM/year at full capacity. Since water in Tijuana is more expensive than that in Mexicali, it is unlikely that Tijuana would reduce imports much compared to agricultural use in the Mexicali Valley.

For minimum environmental flows to the delta from 0 to 20 MCM/month, scarcity is greater when no alternative water sources are available. Willingness to pay for additional transboundary water flows from the United States is quite low for the range of values in the model (Fig. 8). These results resemble shadow value trends for the minimum flow constraint in the CRD (Fig. 6).

It is possible to use these model results as a framework for estimating the perceived economic value of environmental restoration flows for the Colorado River Delta. Figs. 6 and 7 indicate to policy makers the trade-off of economic costs to agricultural and urban uses against environmental flows for each alternative, as a unit cost or as a total cost. A decision maker selecting a particular point on this trade-off curve has implicitly placed an economic value on the marginal environmental flow. These results also can provide reasonable estimates of compensation costs for agriculture due to burdens from environmental flows.

Finally, the models and modeling framework developed here support the integrated understanding and analysis of this complex system. As more details regarding desirable environmental flows, infrastructure options, and cost arise, these can be incorporated into the model and their implications can be explored.

Conclusions

Five major conclusions arise from this work:

1. Economical sources of water for restoring the Colorado River delta can be found among existing water uses in the Mexicali Valley. These transfers can be made by expanding existing water markets in the Mexicali Valley. Marginal costs of environmental flows are about $50/TCM for commonly recommended restoration flows. However, this cost rises to about $80/TCM when recommended flows are roughly doubled.
2. Wastewater reuse facilities have only a small supporting role in supplementing environmental restoration flows for the delta, but may have other water quality benefits.
3. The marginal value of additional Colorado River flows from the United States is small: $13.50/TCM without environmental flows, rising to $24/TCM with commonly recommended environmental flows, and becoming as high as $35/TCM when recommended flows are doubled. Transboundary Colorado River water purchases from the United States could not be supported at these prices. The development of flyway habitat in the CRD may be more cost-effective than dedicating flows to the Salton Sea, to the extent that these habitats are substitutable. This could be explored as an additional value for transboundary water transfers.
4. A regional systems model provides the framework for integrating our understanding of the system and developing insights and implications of this understanding. As our understanding improves with greater experience and more detailed studies, these improvements can be incorporated into this framework and their implications can be explored.
5. The trade-off curves developed from this kind of study could support decision making and economic valuation of environmental flows by decision makers. Unlike traditional valuation techniques for this type of use, water value is estimated from opportunity cost to other uses. One advantage of the approach proposed here is that water for urban and agricultural production is implicit in the valuation. However, economic welfare measures such as change in consumer surplus from different environmental water flow levels could not be evaluated directly, as shadow values of the environmental flows arise from the supply and not the demand side of the implicit general equilibrium model for water in a region.

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