AN OPTIMIZATION MODEL FOR WATER MANAGEMENT IN THE USA-MEXICO CALIFORNIAN BORDER.

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ABSTRACT

Fast growing cities and arid climate characterize northern Baja California, Mexico and Southern California in the United States. This paper presents a quantitative approach to identify promising water management alternatives, to cope with demands northwestern Baja California for year 2025. The California Value Integrated Model (CALVIN) is used as the main analysis tool to undertake this analysis. Economic water demand functions for urban and agricultural water uses in the cities of Ensenada and Tijuana, Baja California were estimated and used as an input for CALVIN. Water supply alternatives for year 2025 in Baja California include expanded infrastructure capacity, wastewater reuse, seawater desalination and aquifer overdraft. Results show that wastewater reuse can significantly reduce projected water scarcity and its costs for year 2025. In contrast seawater desalination seems to be a less promising alternative if its costs remain as high. This systems approach could effectively shed some light on future directions for water planning in this and other hydrologically connected regions including Southern California.

KEYWORDS:

Water management, wastewater reuse, desalination, urban water demand, agricultural water demand, transboundary basins,

INTRODUCTION

Southern California (USA) and Baja California (Mexico) both face water scarcity problems of fast growing urban areas, irrigated agriculture and increasing environmental water demands. Water infrastructure development in the region has resulted in habitat degradation from massive flow diversions and damming of streams. Nevertheless, environmental interest groups and scholars have become influential in the policy and politics of water allocation. Currently, growing cities are increasing their water use relative to agricultural users. Cost effective alternatives for future urban, environmental, and agricultural water supplies are needed. Some specific conflicts and questions involve:

- economic costs to agricultural and urban water users of dedicated restoration flows for the Colorado River Delta ecosystem;
- net economic benefits of water reuse versus seawater desalination versus additional water imports in the coastal areas of Baja California;
- promising hydraulic facility expansions in northern Baja California;
- trans-boundary water issues and opportunities between the US and Mexico along the California border.

These issues pose challenges to urban planners, policymakers, researchers, legislators, and other stakeholders in Baja California, as well as California.

Baja California Mexico is characterized by a rapid 4% population growth rate (CONEPO 2005), economic development, and prominent agriculture. As in California, USA, water has been important to support this development and is a scarce resource for both states. In Baja California the mean annual precipitation is around 145 mm per year compared to the national average of 771 mm (CNA 2004). Most water for border cities and agriculture in northern Baja California comes from the Colorado River (under the 1944 US-Mexico Water Treaty) and groundwater extraction (Cohen and Henges-Jeck 2001). Other cities, such as Ensenada, rely entirely on groundwater, which is affected by seawater intrusion and increasing pumping costs. Water issues in Baja California include water scarcity, salinity, seawater intrusion, aquifer overexploitation, and environmental and water quality degradation . These problems are linked to larger water and economic issues in the state and in the US. Trans-boundary Mexico-US water issues include the lining of the All American Canal in southern California, the overexploitation of the border aquifers, water salinity, wastewater quality, and environmental restoration.

Over time, water management in the northern Baja California region has produced a vast literature regarding alternative water sources and conveyance infrastructure (Luecke et al. 1999; Michel 2002), conservation concerns (Glenn et al. 2001), water rights (Culp 2000), and socioeconomic impacts. However, there has been little systematic analysis of alternatives from a regional perspective that include more flexible water allocation, integrated water resources management, and economic costs and benefits of water use. Most previous studies have focused on local issues without a rigorous economic estimation of the burdens to various water users from different alternatives. Studies urging increasing flows in the CRD, for example, would benefit from adding opportunity costs to urban and agricultural users.

The purpose of this research is to provide a formal quantitative analysis of integrated water resources management for a northern region of Baja California, Mexico. This analysis is then used to identify economically promising water management policies, estimation of water allocation trade-offs among agricultural, environmental and urban uses, estimation of economic effects of different policy and infrastructure alternatives for the region and identification of promising solutions to the region's water-related economic and environmental problems were included using water demand projection for year 2025. The cities of Ensenada and Tijuana-Rosarito along with Ensenada agricultural regions of Guadalupe and Maneadero are the case study of this paper. Results indicate that keeping the

METHODS

The CALVIN Model

Building upon a CALVIN model for Ensenada (Medellin-Azuara et al. 2007b), the urban region of Tijuana/Rosarito was added along with existing and future conveyance and storage infrastructure. The California Value Integrated Network Model (CALVIN) offers a systematic approach to study such complex water resource management problems. The CALVIN model is a systems analysis tool, which has been developed and successfully applied in California. The model is a network flow optimization model which integrates an engineering description of a water management system, economic descriptions of water use demands and costs, and specific environmental and water allocation policies to identify promising solutions to regional water resource problems (Draper et al. 2003). CALVIN applications in California include users' willingness to pay for additional water, the economic values of conjunctive use, economic cost of environmental restrictions, economic impacts of dam removal, facility expansions, conveyance, and water transfers (Jenkins 2004; Medellin-Azuara et al. 2007a; Null and Lund 2006; Pulido-Velazquez et al. 2004; Tanaka et al. 2006).

CALVIN results go beyond simple cost-benefit analysis or net present value project evaluation. Modeling using CALVIN includes the economic value of water for different uses based on water scarcity and supply costs. Based on economic costs and benefits, CALVIN can identify economically promising management activities integrated from a broad array of options such as additional conveyance capacity, water reuse and desalination capacity, deregulation, water markets, water conservation, and opportunity costs for water users under different environmental, hydrologic, infrastructure scenarios.

Urban Water Use

With rapid population and economic growth, urban water supply is a pressing issue. Various alternatives are available, differing somewhat among individual cities. Alternative water sources for the city of Tijuana include expansion of the existing Colorado River-Tijuana aqueduct {Michel, 2002 #171}. Seawater desalination is being considered for coastal areas such as Tijuana, Rosarito and Ensenada (CNA 2005). Wastewater reclamation for aquifer recharge is another source of water to ameliorate scarcity and reduce groundwater extraction costs (Mendoza *et al.* 2004). Nevertheless, most studies to date emphasize a local operations perspective using traditional project evaluation by cost effectiveness analysis.

Urban demands for the region and scarcity costs were obtained from an econometric model of residential demand for the cities of Tijuana and Ensenada based on Medellin-Azuara (2006). Commercial, industrial and other uses were assumed to be highly inelastic approaching to fixed demands. The locations use an increasing block rate structure to charge residential, industrial and commercial customers. In the estimation, a two-step ordinary least squares regression using instrumental variables for the last block of consumption unit price and a Taylor-Nordin difference variable (Nordin 1976; Taylor 1975). Other independent variables in the regression include reference evapotranspiration, season dummies and precipitation.

From the econometric model a price-elasticity of demand for water per season was obtained. From there, a constant-elasticity of demand function was built following Young (2005) and Jenkins (2003). The demand curve was integrated numerically to get economic costs of shortage in the urban locations.

Data for six years (2000-2005) of aggregate water consumption per block rate for residential, commercial and industrial uses was provided by the local utilities for Ensenada (CESPE) and Tijuana/Rosarito (CESPT). Table 1 summarizes water demands in year 2005 for both locations. For Ensenada, an amalgam or residential and all other uses was used in the model. For Tijuana, residential and non-residential uses were segregated. Water demand for the cities was projected for year 2025 using both the utilities and the National Population Council (CONAPO) estimates.

Table 1 Annual Water consumption in thousand cubic meters (Sources CESPE, CESPT).

Use	Ensenada	Tijuana/Rosarito
Residential	13,400	56,876
Commercial	1,179	6,978
Industrial	830	7,753
	15,409	**71,606**

Results indicate that residential uses in Ensenada are moderately responsive to changes in water rates. Elasticity for the warm months (April-August) was close to -0.6 whereas that for non-warm months was -0.3. In contrast, the city of Tijuana appears to be irresponsive to price changes with an roughly year-wide elasticity of -0.13.

Agricultural Water Use

The valleys of Guadalupe and Maneadero, in the Ensenada subregion, are second to Mexicali in importance for agricultural water use, relying on groundwater without access to Colorado River water. Approximately 23 to 26 thousand acre-feet of water are extracted annually from the Guadalupe aquifer; roughly one third of the extraction is used as potable water supply for the city of Ensenada, while two thirds are used for agricultural activities in the valley, mainly wineries (Daesslé et al. 2006). Despite the economic importance of agriculture in these three areas of Baja California, urban uses continue to expand. Water use from agriculture may decrease by almost 4% from 2002 to 2025 according to the CNA (2002).While world prices of crops, operation costs and other human factors may affect agricultural water demand, the economics of tradeoff of water and cost allocation among agricultural and urban water uses is becoming important.

CALVIN includes water scarcity cost functions from two peripheral demand models for agricultural and urban water uses. The agricultural demand model for Guadalupe and Maneadero Valleys in Ensenada was adapted and developed from the Statewide Agricultural Production model (SWAP) after Howitt (2001). Groundwater irrigation is the main water source for both locations, pumped from the Guadalupe and Maneadero aquifers.

SWAP uses positive mathematical programming (Howitt 1995) that deductively estimates water economic value by restricting water availability and taking the LaGrange multiplier on the constraint. A derived demand curve is constructed from the obtained set of multipliers and, is later integrated numerically to provide water scarcity cost required by CALVIN for agricultural demand uses following the appendixes in Medellin-Azuara (Medellin-Azuara 2006).

Cost and production information for the agricultural water demand models in Guadalpe and Maneadero was provided by the regional offices of the Agriculture Ministry (SAGARPA) and the National Water Commission (CNA). Three years of observations on cultivated land, yields, water, labor, supplies and prices were used. Table 2 summarizes the cultivated land for the crop mix in each region. The crop mixes for both agricultural regions correspond to roughly 82% of the total water use. Thus scarcity cost functions were scaled up to represent the total estimated water use for each region. The rationale for this assumption is the highest productive uses of water are well represented by the SWAP crop mixes and would not be part of the remaining 18% of water.

Table 2 Crop mix and cultivate land (in hecteres) for the agricultural demand model.

Crop	Maneadero	Guadalupe
Alfalfa	163	259
Asparagus	64	
Brocoli	72	
Flowers	211	47
Grape		1,403
GreenOnion	104	
Olives	279	981
Pea	254	
Peper	58	37
Radish	84	
Tomato	450	216
Zucchini	112	43
Total	1,850	2,984

SWAP for Baja California, provides shadow values for agricultural water use in Guadalupe and Maneadero. Although applied water varies by month, the model assumes that the marginal value of water is the same for all months as a result of the profit-maximizing behavior of the farmers Figure 1 Shadow value of water in agriculture for Guadalupe and Maneadero..

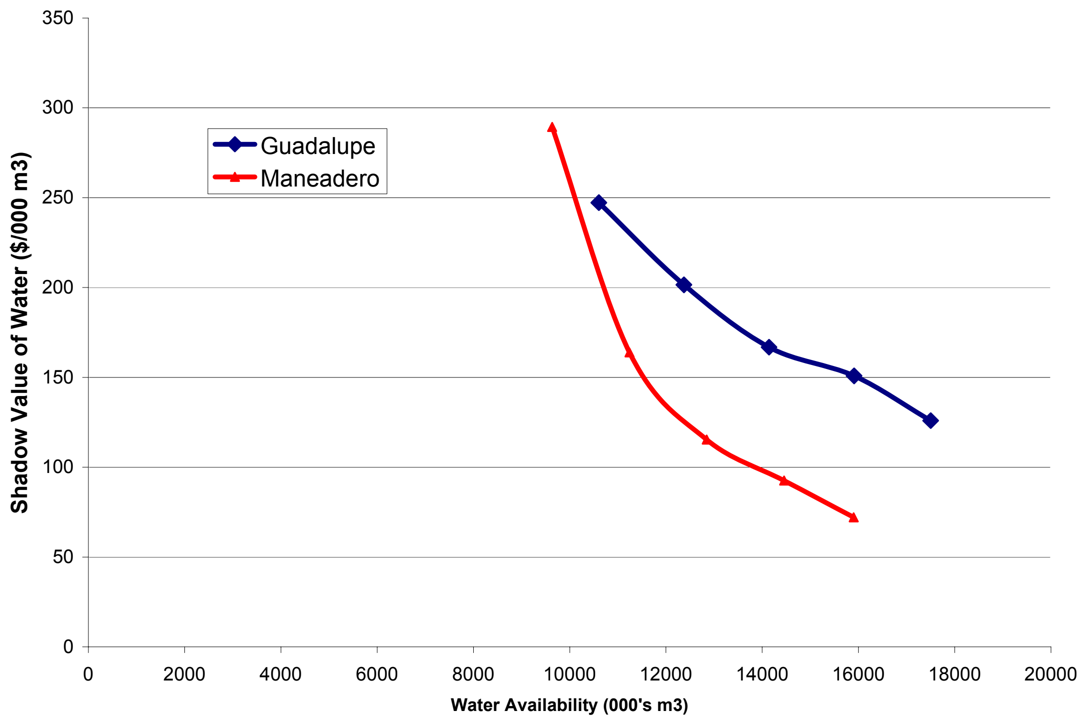

Figure 1 Shadow value of water in agriculture for Guadalupe and Maneadero.

At full water availability levels, the shadow value of water for agricultural uses in Guadalupe and Maneadero are respectively $72 and $125 dollars per thousand cubic meters ($/TCM). With water shortages of sixty percent, this shadow value can be as high as $290 dollars per TCM. Maneadero shadow value compares to that obtained in some irrigation subdistricts in the Mexicali Valley (Medellin-Azuara et al. 2007a), the largest agricultural production location in Baja California. However, shadow value of water for Guadalupe is substantially higher.

A CALVIN Model for Ensenada and Tijuana-Rosarito

In this investigation, the water management tool called CALVIN (California Value Integrated Network) is used to model water management alternatives to meet future demands in the cities of Tijuana and Ensenada, Baja California, Mexico. Figure 2 is a map of showing spatial locations of demand sites in CALVIN Region 6, Baja California.

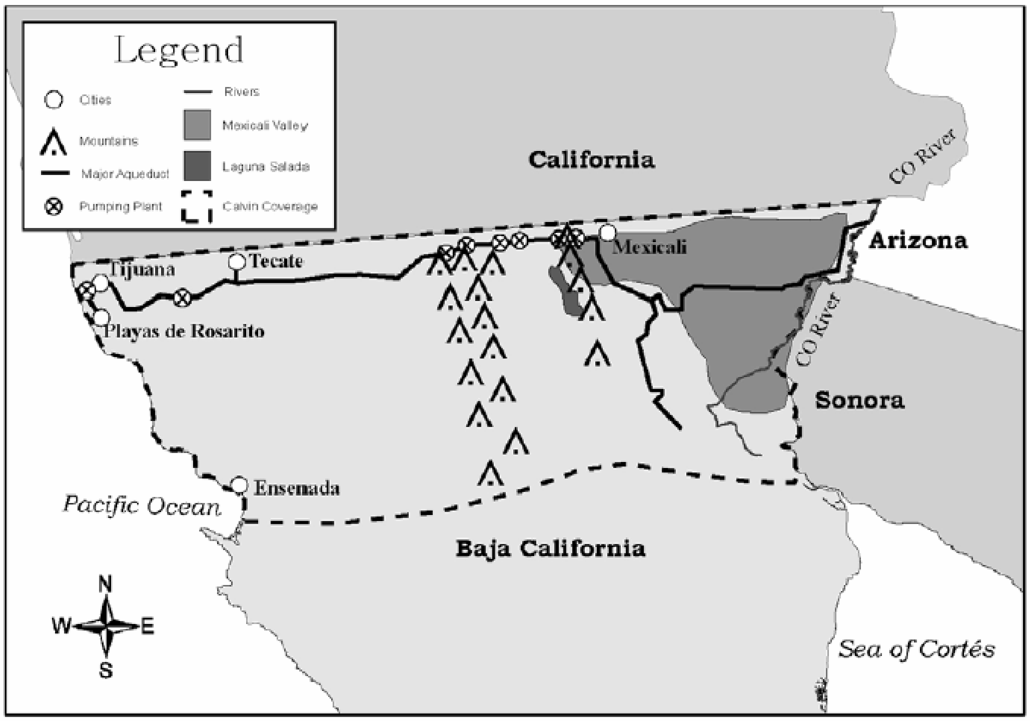

Figure 2 CALVIN Baja California region (after Malinowski 2004)

Figure 3 shows a simplified representation of CALVIN Region 6 that includes nodes an links following previous CALVIN studies ((Jenkins et al. 2001). Ovals represent demand locations, upside triangles are reservoirs and downside triangles are aquifers. Urban water demand nodes for this study include Tijuana-Rosarito residential and non-residential, and Ensenada. Agricultur in Ensenada is grouped in the Guadalupe and Maneadero Valleys. Groundwater sources include the aquifers of Tijuana-Alamar, La Mision, Guadalupe, Maneadero and Ensenada. Three reservoirs are included namely Abelardo L. Rodriguez (ALR), El Carrizo and Zamora. Potable water plants an a set of wastewater treatment plants were considered in the model but not are not shown in the simplified schematic (Figure 3).

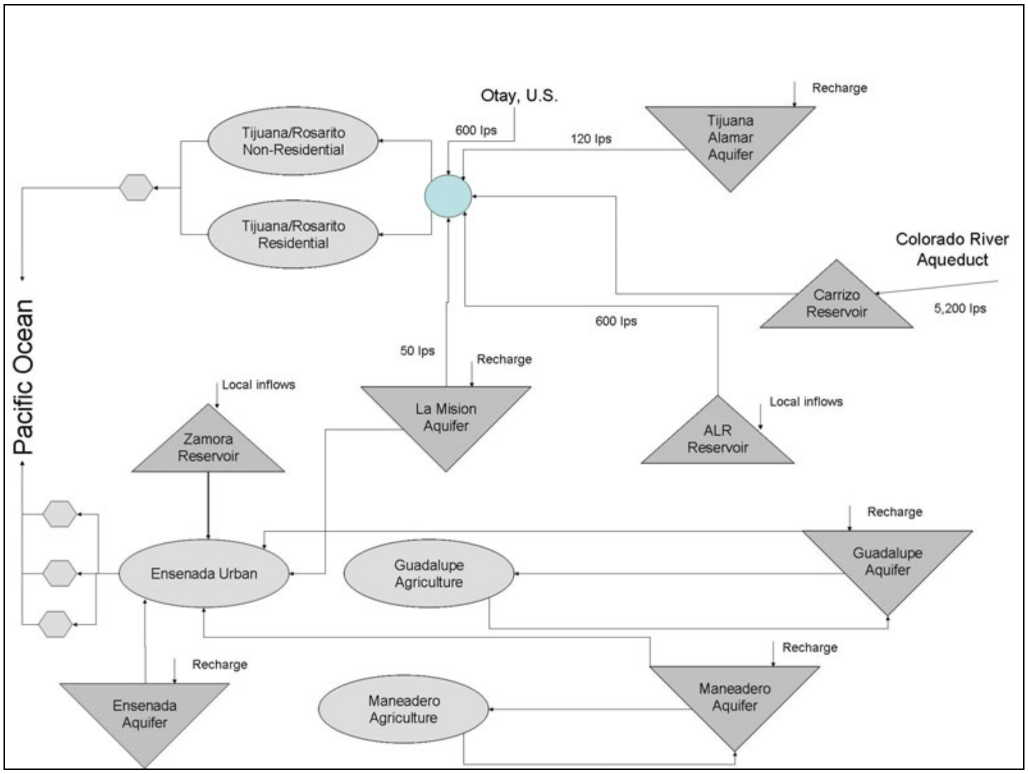

Figure 3 Simplified CALVIN Region 6 schematic for Ensenada, and Tijuana-Rosarito.

Hydrology and Model Calibration

Time series of inflows to the aquifers were obtained from CNA studies on groundwater. Local inflows to reservoirs were provided by CNA as well. El Carrizo reservoir is mainly for buffer inflows from the Colorado River-Tijuana Aqueduct.

Model calibration consisted in the representation of actual and planned water deliveries to the cities of Tijuana and Ensenada as well as agriculture deliveries. The calibration exercise provided a basis for identifying particularly important data gaps and uncertainties.

Water Management Alternatives for Ensenada and Tijuana-Rosarito

Model runs were undertaken to simulate planned allocation for the year 2025 with current management plans (base-case) and diverse water management policies, listed in Table 3. Water management policies were chosen following recommendations from the Tijuana Master Plan (Camp Dresser & McKee Inc. - CDM, 2003) and the Study of Water Markets for Baja California (CNA, 2005).

Table 3 Description of water management policies for the Tijuana and Ensenada region.

Run	Aquifer overdraft?	Wastewater reuse?	Seawater desalination?	Aqueduct @ 5,200 l/s	Ensenada enforced allocation?
A					
B					
C					
D					
E					
F					

A. Base-case with overdraft permitted
B. Worst-case scenario; no expansion of aqueduct (current capacity = 4,000 l/s)
C. Base-case without aquifer overdraft
D. Wastewater reuse allowed for Ensenada's El Naranjo, El Gallo and El Sauzal plants and Tijuana's International and San Antonio de los Buenos plants; Colorado River Delta minimum allocation
E. Colorado River water allocation to Ensenada enforced (285 l/s).
F. Wastewater reuse, seawater desalination (250 l/s for Ensenada and 3,225 l/s for Tijuana)

RESULTS AND DISCUSSION

Results for the six water management options chosen for the Tijuana-Ensenada region are presented in Table 4. In all cases urban demand for Ensenada is 100% reached due to the fact that Ensenada's water supply comes from local aquifers that are being overexploited. Such is the case of the base-case, where aquifers overdraft is permitted, resulting in low scarcity for the agricultural valleys of Maneadero and Guadalupe. Scarcity for Tijuana is present due to infrastructure limitations, despite accounting for the increase in the Colorado River-Tijuana aqueduct capacity to 5,200 l/s (from current 4,000 l/s).

Nevertheless, sustainable water management options shouldn't allow for the overexploitation of aquifer. If aquifer's overdraft wouldn't be permitted (Table 4, column C), the city of Ensenada would still receive its required quota of water but the agriculture regions of Maneadero and Guadalupe would present scarcity, particularly the former. Due to the fact that approximately 6% of the water supply to Tijuana/Rosarito comes from aquifers, the scarcity in the region would not be affected.

If no overdraft was permitted and the infrastructure for the expansion of the aqueduct is not built, meaning that Tijuana/Rosarito would only be receiving the current 4,000 l/s (Table 4, Column B), the scarcity in the region would be severe, mainly in Maneadero but with greater impact in Tijuana-Rosarito. Combined scarcity costs of approximately 257 million dollars per year would be reached, from which 235 million pertain to residential water use in Tijuana-Rosarito.

The reuse of wastewater in the region includes the following: reuse from Ensenada's three wastewater treatment plants (El Naranjo, El Gallo and El Sauzal) in activities such as the irrigation of crops at Guadalupe and Maneadero, the recharge of the Guadalupe and Maneadero and the recharge of the Zamora reservoir; in Tijuana/Rosarito, reuse includes the options of sending 1,100 l/s of effluent from the San Antonio de los Buenos plants to recharge the Abelardo L. Rodríguez reservoir and the availability of 350 l/s of effluent from San Diego's South Bay International Plant (that only treats wastewater from Tijuana/Rosarito) for the recharge of the Alamar/Tijuana aquifer. Such measures would cause a sharp decrease in the scarcity in Maneadero, Guadalupe, Tijuana's residential demand and the non-scarcity for Tijuana's non-residential demand (Table 4, Column D), despite the allocation of minimum restoration flows for the Colorado River Delta of 8 MCM/month.

Table 4 Scarcity, scarcity costs and willingness to pay for water management options in the Tijuana/Rosarito and Ensenada regions.

		A	B	C	D	E	F
Scarcity costs ($K/y)	Urb-Ens	0.0	0.0	0.0	0.0	0.0	0.0
	Man	132.0	2,718.8	2,414.9	47.6	88.1	47.6
	Gpe	117.4	596.7	596.7	363.0	596.7	363.0
	Res-TJ	37,292.6	235,617.1	37,292.6	26,819.3	42,475.7	13,009.5
	NR-TJ	7,560.6	18,705.9	7,560.6	0.0	7,560.6	0.0
	Total	45,102.6	257,638.5	47,864.8	27,229.9	50,721.1	13,420.1
Average Willingness to pay ($/1000 m^3)	Urb-Ens	0.0	0.0	0.0	0.0	0.0	0.0
	Man	79.5	211.5	203.8	39.9	67.2	39.9
	Gpe	20.0	69.6	69.6	48.5	69.6	48.5
	Res-TJ	2,138.5	10,479.50	2,138.5	1,292.4	2,321.40	743.2
	NR-TJ	1,531.3	3,797.60	1,531.3	0.0	1,531.30	0.0
Scarcity (Mm^3/y)	Urb-Ens	0.0	0.0	0.0	0.0	0.0	0.0
	Man	1.6	14.0	12.7	0.6	1.1	0.6
	Gpe	1.4	5.6	5.6	3.9	5.6	3.9
	Res-TJ	21.4	44.9	21.4	15.7	23.9	10.8
	NR-TJ	1.2	3.1	1.2	0.0	1.2	0.0
	Total	25.6	67.6	40.9	20.2	31.8	15.3

NOTES:
Urb-Ens: urban demand for Ensenada
Man: agriculture demand for Maneadero valley
Gpe: agriculture demand for Guadalupe valley
Res-TJ: residential demand for Tijuana/Rosarito
NR-TJ: non-residential (ie. industrial and commercial) demand for Tijuana/Rosarito

Currently, Ensenada has an allocation of 285 l/s from the overall Colorado River water allocated for Mexico. However, this allocation is being used to cover for Tijuana/Rosarito demands. Water managers in Ensenada have continually expressed the desire to use this volume of water for Ensenada, which could help decrease the dependence of Ensenada on aquifers overexploitation.

Although no infrastructure is currently available to make use of such share, this was included in run E (Table 4) to determine its effect on the regional water allocation. It can be observed that, as expected the scarcity for the Maneadero aquifer would decrease, meaning that more water would be available for agricultural use. In Tijuana/Rosarito, such measure would cause an increase in the scarcity for both the residential and non-residential demand.

Finally, column F in Table 4 presents the results if all promising water management options were to be built, including wastewater reuse (as explained in case D) plus the construction of seawater desalination plants, specifically a 250 l/s plant for Ensenada (its construction currently being contracted) and a 3,225 l/s plant for Tijuana, as suggested by Tijuana's Master Plan (CDM 2003). Such measures would allow for the smallest scarcity in the region, meaning that it would be one of the most beneficial. A scarcity of 10.8 Mm^3/y would still be present for Tijuana's residential use due to the high cost of desalination (here calculated at \$1.3 dollars per m^3). Since the CALVIN model allocates water in terms of the optimization of economic value of the resources and the willingness to pay is approximately \$743 dollars per 1000 m^3 it doesn't seem viable to allocate water to this demand, as this would cause a loss and not an economic gain.

Such results emphasize the fact that wastewater reclamation and reuse for Tijuana/Rosarito and Ensenada is one of the most economically promising alternatives to meet future water needs, only behind the increase in water imports. Other options like seawater desalination are not economically viable *per se*, and would have to be combined with an integral management of water within the Northern Baja California region.

All models have limitations and this is not less true for CALVIN whose main sources of limitations have been identified as data quality, system simplifications and non-exhaustive economic representation (Jenkins 2004). In particular, an important fact to consider is that the model assumes that operational and allocation changes suggested are possible institutionally. Yet this might not be possible due to the complexity of water management in Mexico in general and Baja California in particular.

Nevertheless, having this type of analytical tool for Baja California will allow more definitive answers to many other water and environmental issues for this region. However, precise applications of optimization insights will always require further testing and refinement by more detailed simulation studies. Further work will include the link to the existing CALVIN model for Mexicali and California (USA) that will allow for a better quantitative exploration of cross-border water management issues.

CONCLUSIONS

Measures to build the required infrastructure for water demand in the regions of Tijuana/Rosarito and Ensenada have to be taken in order to avoid urban and agricultural scarcity. Water supply from the overexploitation of aquifers could be substituted by desalinated water and/or recycled wastewater. Hence wastewater reclamation and reuse for Tijuana/Rosarito and Ensenada is one the most economically promising alternative to meet future water needs, only behind the increase in water imports. Other options like seawater desalination are not economically viable *per se*, and would have to be combined with an integral management of water within the Northern Baja California region.

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