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Virtues of simple hydro-economic optimization: Baja California, Mexico

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ABSTRACT

This paper uses simple hydro-economic optimization to investigate a wide range of regional water system management options for northern Baja California, Mexico. Hydro-economic optimization models, even with parsimonious model formulations, enable investigation of promising water management portfolios for supplying water to agricultural, environmental and urban users. CALVIN, a generalized hydro-economic model, is used in a case study of Baja California. This drought-prone region faces significant challenges to supply water to agriculture and its fast growing border cities. Water management portfolios include water markets, wastewater reuse, seawater desalination and infrastructure expansions. Water markets provide the flexibility to meet future urban demands; however conveyance capacity limits their use. Wastewater reuse and conveyance expansions are economically promising. At current costs desalination is currently uneconomical for Baja California compared to other alternatives. Even simple hydro-economic models suggest ways to increase efficiency of water management in water scarce areas, and provide an economic basis for evaluating long-term water management solutions.

1. Introduction

Water resource systems analysis is often assumed to be an expensive, time-consuming process that yields ambiguous results. This need not always be the case. Here we examine how management insights and tradeoffs can come from a simple, but sufficiently complex, hydro-economic model for Baja California, Mexico. Commonly, intertied networks of surface and groundwater reservoirs, conveyance and treatment infrastructure, and demand areas are represented as a system with a set of hydrological conditions, institutional constraints and water use levels. Such system representations are enriched with the addition of economic benefits and costs (water scarcity costs or economic delivery values and operation costs) to the system representation, to provide a combination of hydrologic, economic, and engineering insights for water management.

Hydro-economic optimization models can provide both hydrologic and economic results and integrated insights for water management and allocation. For example, marginal values for facility expansions indicate system-wide cost reductions from small facility expansions. Furthermore, shadow values of water indicate marginal willingness to pay for water to help identify promising water management portfolios from millions of potential portfolios. In contrast, simulation models of water resources may provide more detailed and accurate representation of a single portfolio. Ideally, simulation modeling can help test and refine promising policies and portfolios identified using optimization (Lund and Ferreira, 1996).

1.1. Hydro-economic optimization of regional water resource networks

Since the earliest applications of systems analysis to water resources management, economic objectives and constraints have frequently been used in models of real systems (Loucks et al., 1981; Maass et al., 1962). Hydro-economic models integrate regional hydrologic, engineering, environmental and economic aspects of water resources systems within a single coherent framework, to examine water management for diverse types of economic values. Recent hydro-economic research has been described by Jakeman and Letcher (2003), Lund et al. (2006), Cai (2008), Heinz et al. (2007), Brouwer and Hofkes (2008) and Harou et al. (in press).

Most hydro-economic models share basic components of hydrologic flows, water management infrastructure, economic water demands, operating costs, and operating rules. Since Maass et al.

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(1962), water resource systems have been modeled as networks of storage and junction nodes joined by conveyance links representing river reaches, canals, pipelines, etc. Water use and cost locations also are represented as links. The network format is straightforward for simulation and allows for efficient and parsimonious model formulations. Boundary conditions in the form of inflows and outflows can occur anywhere in the network (Letcher et al., 2007).

In the approach followed in this paper (Draper et al., 2003), water management is driven by a deterministic multi-period optimization model that maximizes net benefits from urban and agricultural deliveries (or minimizing net costs of water scarcity and operations). The method is implicitly stochastic if long historical or synthetic inflow time series are used to represent a wide range of potential conditions. Net benefit functions (or scarcity costs) are derived from economic water demand curves. This approach is classical in hydro-economic modeling (Bear and Levin, 1970; Gisser and Mercado, 1972; Noel and Howitt, 1982; Booker and Young, 1994; Ward and Lynch, 1996; Rosegrant et al., 2000). Model results include time series of storage and flow decisions throughout the network. Such optimized results directly reflect model formulation, network topology and benefit (or penalty) functions for each demand. Results enable inferences about potentially beneficial operating rules and management practices (Lund and Ferreira, 1996). Because the objective function is economic, shadow values (shadow prices) provide the marginal opportunity costs to the entire system of flow constraints such as infrastructure limits and minimum ecological flows. These shadow values are given by the Lagrange multipliers for each flow constraint.

1.2. Case study: Baja California Mexico

Baja California's northern region (Fig. 1) will struggle in the coming decades to supply water for agriculture, cities and ecosystems. Table 1 summarizes water management challenges faced by this region. Most of this extremely arid region's water supplies are from the Colorado River and aquifers. The Mexican border cities of Tijuana–Rosarito, Tecate, and Mexicali depend mostly on the Colorado River. Nearly 200 million cubic meters per year (Mm^3/yr) of groundwater in Baja California are devoted to urban uses. Currently, the coastal city of Ensenada relies mostly on local aquifers for both agriculture and urban demands. Cities in Baja California are increasing their water use, with relatively constant agricultural use. Thus, cost-effective portfolios are needed for future urban, environmental, and agricultural water supplies.

Baja California borders on the states of California and Arizona in the United States. In Baja California, the Tijuana–Rosarito area (Fig. 1) dominates urban use (currently in 105 Mm^3/yr) followed by Mexicali (86 Mm^3/yr). Most of this water is supplied by the Colorado River–Tijuana aqueduct (CRTA) with an annual capacity of 126 Mm^3/yr (thick dotted line in Fig. 1), supplying 3.3 Mm^3/yr to Tecate as well. Ensenada (16 Mm^3/yr), currently is supplied by local aquifers and is unconnected from its Colorado River allocation of 8 Mm^3/yr. The largest regional water user by far is irrigated agriculture in the Mexicali Valley, which applies at least 2000 Mm^3/yr from surface and groundwater sources. Table 2 summarizes current and projected water demands for northern Baja California.

Environmental flows for the Colorado River Delta (CRD) had not been a concern until recently; however, about 40 Mm^3/yr of instream flows with pulse flows of 300 Mm^3/yr every four years are required to keep the delta's ecosystems healthy (Glenn et al., 2001). The delta currently survives partly due to operational water releases from the US beyond the 1994 treaty quota for Mexico.

In Mexico, water is a federal jurisdiction. Under the National Water Law of 1992 (NWL reformed in 2004), water users are granted water use rights or time-limited concessions, rather than water rights. The National Water Commission (or CNA) oversees the NWL and issues water use right titles. Agricultural users are supplied as members of water user associations or granted water user rights for private wells. States have local utilities for urban water supply, which also receive water use rights from CNA.

Surface water in this region is governed mostly by the 1944 binational US–Mexico water treaty, which provides Mexico with at least 1850 Mm^3/yr of Colorado River water. Rainfall is insignificant and hardly exceeds 100 mm/yr in Mexicali. Surface water from the Colorado River is conveyed through hundreds of kilometers of canals in Irrigation District 014 in the Mexicali Valley, and to the west through the Colorado River–Tijuana aqueduct (CRTA). The CRTA has storage to hold about three months of water for

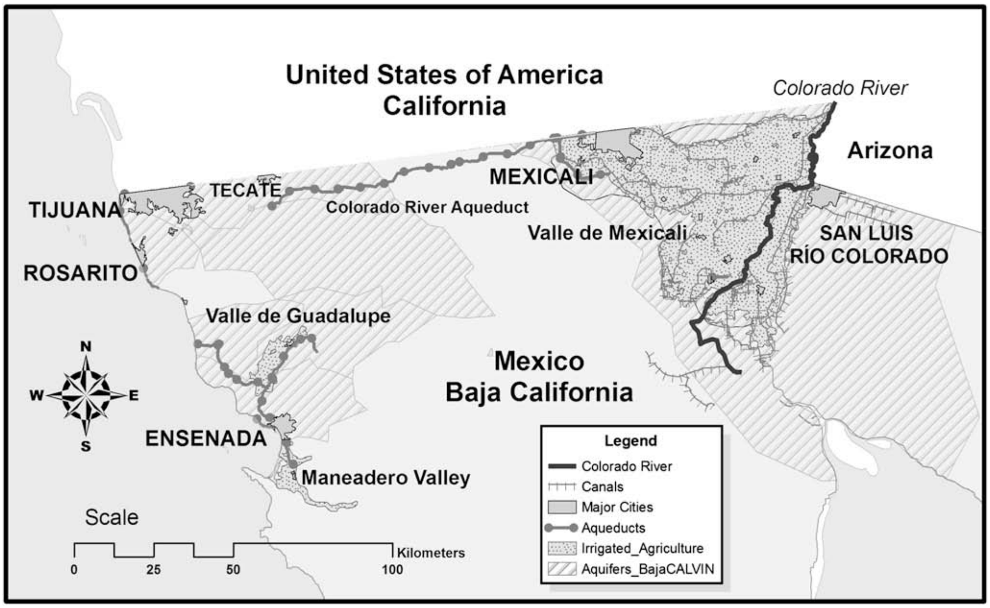

Fig. 1. Baja CALVIN coverage Map.

Table 1
Water management challenges and portfolios for securing water supply for northern Baja California by sub-region.

Region	Characteristics	Water management challenges and portfolios
Ensenada	• Water mostly from local aquifers. • High value agriculture. • Exceptional wastewater treatment capabilities.	• Groundwater overdraft and the problems accompanying saline intrusion in some aquifers. • Sustain future urban demands without threatening agriculture. • Potential sources include seawater desalination, wastewater reuse and a new aqueduct to wheel water from the Colorado River.
Mexicali–San Luis Río Colorado	• Extreme arid region. • Water uses are supported by the Colorado River diversions and groundwater pumping. • Colorado River Delta requires water for ecosystem functions.	• Water supply for urban growth with minimum harm to agriculture. • Wastewater reuse from the two main wastewater treatment plants, and supplying water for restoration in the Colorado River Delta. • Sources include water markets and reclaimed wastewater.
Tijuana–Rosarito	• Water demands expected to exceed current supply capacities in a few years. • An expanded aqueduct can only partially fulfill expected growth.	• Water supply for urban growth. • Sources include additional infrastructure such as an expanded Colorado River–Tijuana aqueduct, increased groundwater capabilities, wastewater reuse and seawater desalination.

Tijuana–Rosarito (El Carrizo reservoir's 34.4 Mm^3 capacity). In extreme drought, the Colorado River–Tijuana system supplies about 95% of Tijuana–Rosarito's water use (Malinowski, 2004).

Systematic analysis of a wide range of water management portfolios from a regional perspective in Baja California remains largely unexplored. This paper provides insights on promising water supply portfolios for Baja California through a formal integrated analysis of the region's water management. CALVIN (CALifornia Value Integrated Network), a network flow optimization model, was used for this analysis under estimated 2025 Baja California water demands for what is now called Baja CALVIN.

2. Methods

The CALVIN model supports integrated study of large-scale water resource systems. It employs the HEC-PRM "Prescriptive Reservoir Model" software as its computational and organizational core (Draper et al., 2003; USACE, 1999). HEC-PRM uses an efficient generalized network flow linear optimization formulation that represents the system as a network of nodes and links. Linearity guarantees a globally optimal solution while use of the network flow algorithm is faster than a standard linear program. The model minimizes costs subject to flow continuity at nodes and capacity constraints on links, written as:

$$\mathrm{Min} \sum_t \sum_i \sum_j c_{ij} X_{ijt}$$

subject to

$$\sum_i X_{ijt} = \sum_i a_{ijt} X_{ijt} + b_{jt} \quad \forall j, t,$$
$$X_{ijt} \le u_{ijt} \quad \forall i, j, t, \quad X_{ijt} \ge l_{ijt} \quad \forall i, j, t,$$

where X_{ijt} is flow from node i towards node j (link ij at time t), c_{ij} = unit cost of flow through link ij (scarcity costs or operating costs), b_j = external flows to node j, a_{ijt} = gain/loss coefficient on flows in link ijt, u_{itj} = upper bound (capacity) on link ijt, and l_{itj} = lower bound on link ijt (minimum instream flows). Scarcity is defined as the difference between the water deliveries given by X_{ijt} and the resulting water use if supplies were unrestricted and free (Jenkins et al., 2004). This nominally unrestricted use is also called the target demand. Scarcity costs represent the economic losses of delivering less water than the target demand. Operating costs include unit costs for conveyance and water treatment, typically without fixed or capital costs. The network flow formulation precludes other constraint forms to represent more detailed physical processes such as groundwater hydraulics or hydrologic routing. The formulation considers storage as flow over time and optimizes over the entire time horizon (presuming hydrologic foresight).

Table 2
Current and projected average annual water demands for northern Baja California (source: Medellin-Azuara et al., 2008b).

Location	Current demand (2000–2005) (Mm^3/yr)	2025 Demand (Mm^3/yr)
Urban		
Ensenada	15.4	20.6
Mexicali	86.0	100.9
Tijuana–Rosarito	104.5	216.3
Agricultural		
Guadalupe	17.5	17.5
Maneadero	15.9	15.9
Mexicali	1968.0	1968.0
Total	2207.3	2339.2

The CALVIN model has been applied in California to study the potential of water markets, gains from conjunctive use operations, climatic change, infrastructure expansions, and conservation issues (Draper et al., 2003; Harou and Lund, 2008; Medellin-Azuara et al., 2008a; Pulido-Velazquez et al., 2004). This study merges previous subregional CALVIN models in Baja California described in Medellin-Azuara et al. (2008b) into a comprehensive Baja CALVIN model. A simplified schematic of Baja CALVIN appears in Fig. 2. A detailed schematic is available at: http://cee.engr.ucdavis.edu/BAJACALVIN.

In the water resources network for northern Baja California (Fig. 2) ovals represent demand locations, upside triangles are reservoirs and downside triangles are aquifers. Five urban demand locations are considered: San Luis Rio Colorado, Mexicali, Tecate, Tijuana–Rosarito and Ensenada. Irrigated agriculture in Mexicali, as well as Maneadero and Guadalupe in Ensenada comprise agricultural demands. Four aquifers for Ensenada, two for Tijuana and the Mexicali/Mesa Arenosa system in the east comprise the region's groundwater system. No major surface reservoirs exist in northeastern Baja California. However, Tijuana has two major reservoirs: El Carrizo, which stores water from the Colorado River aqueduct, and the Abelardo L. Rodriguez, which delivers local inflows and is used for flood control. Water and wastewater treatment facilities at each urban center also are considered. Finally, the Hardy River and Colorado River Delta with inputs from unclaimed instream flows from the Colorado River and agricultural drainage are ecological water uses in the region.

2.1. Urban water demand

Urban water demands for the region and scarcity costs were obtained from an econometric analysis of residential demand for the cities of Ensenada, Mexicali, Tijuana and San Luis Rio Colorado

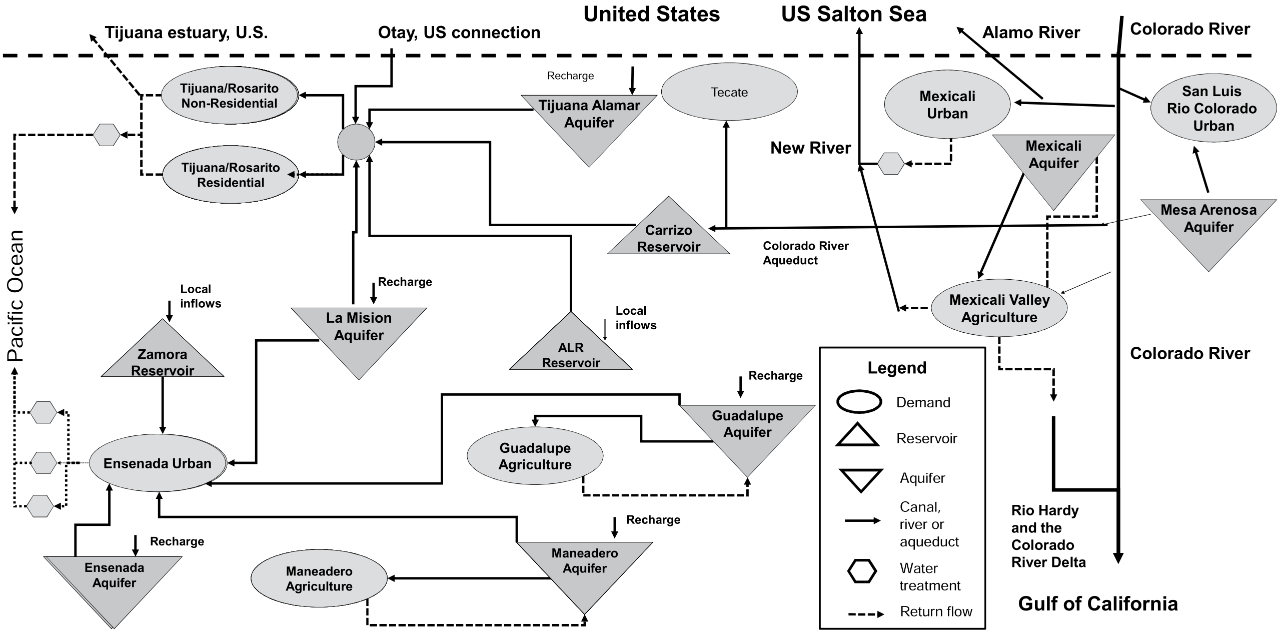

Fig. 2. Simplified schematic of Baja CALVIN (adapted from Medellín-Azuara et al., 2008).

(Medellin-Azuara et al., 2008b). Water uses in Tecate and non-residential uses for all cities were assumed to be much less elastic, implying approximately fixed water use. Explanatory variables in the econometric estimation included unit price, evapotranspiration, seasonal dummies and precipitation. With the estimated price elasticities, a constant-elasticity demand function was built (Jenkins et al., 2003). The demand curve was integrated for the total water scarcity costs (economic loss) for each water demand. Water scarcity costs are part of the objective function (term c_{ij}) used to weigh tradeoffs involved in water allocations. Water consumption panel data (2000–2005) from local utilities was used. This panel was disaggregated by per block rate for residential, commercial and industrial locations. Price-elasticity of demand for water by econometric estimation ranged from -0.18 for Tijuana to -0.86 for Mexicali, suggesting a 1% increase in water price would decrease water consumption by 0.18 and 0.86% respectively (Medellin-Azuara et al., 2008b).

2.2. Agricultural water demand model

Agricultural water demands and scarcity costs were estimated in a separate optimization model (Medellin-Azuara et al., 2009), using positive mathematical programming (Howitt, 1995) to estimate shadow values of water in agriculture. Shadow values of water represent the willingness to pay for the next unit of available water. Groundwater from the nearby aquifers is the main source for Maneadero and Guadalupe irrigation. From 28 to 32 Mm^3/yr of water are extracted from the Guadalupe aquifer, supplying roughly one third for potable water supply for the city of Ensenada and two-thirds for agriculture in the Guadalupe valley, which supports the most important wineries in the country (Daesslé et al., 2006; Mendoza-Espinosa et al., 2008). Despite the economic importance of agriculture in these three areas, urban uses continue to expand. Water use for agriculture may decrease by about 4% from 2002 to 2025 (CNA, 2002).

Cost and production information for agricultural water demand models in Guadalupe and Maneadero were provided by the regional offices of the Agriculture Ministry (SAGARPA) and the National Water Commission (CNA). At full water availability, the shadow value of water for agriculture in Guadalupe and Maneadero are respectively \$72 and \$125 dollars per thousand cubic meters (\$/TCM). With water shortages of 60%, this shadow value can be as high as \$290 per TCM. These shadow values of water in agriculture may equal system-wide agricultural marginal willingness to pay for water in the absence of other operating and scarcity costs. Maneadero shadow values of water in agriculture are comparable to some irrigation subdistricts in the Mexicali Valley (Medellin-Azuara et al., 2007), with substantially higher marginal values of water for Guadalupe.

2.3. Hydrology and model calibration

Hydrology for the northeast of Baja California is relatively simple, with no surface water storage in the east, operationally reliable water deliveries from the US, stable and well controlled pumping from the Mexicali aquifer, and almost no rainfall. Time series of surface and aquifer inflows were obtained from CNA studies (CNA, 2006). El Carrizo reservoir mainly redistributes Colorado River–Tijuana aqueduct deliveries. Model calibration consisted of representing actual and planned water deliveries east of Mexicali to the cities of Tijuana–Rosarito and Ensenada and agriculture. For this paper, overdrafted aquifers are those whose extraction exceeds recharge over a long period. CNA (2004) lists the Ensenada, Guadalupe and Maneadero aquifers as overexploited. Policies prohibiting overdraft restricted end-of-period groundwater storage in the aquifer to equal initial storage. Calibration provided a basis for identifying important data gaps and uncertainties.

2.4. Water management portfolios and modeling approach

Table 1 summarizes the main water issues per sub-region. Increased groundwater pumping, an expanded Colorado River–Tijuana aqueduct, wastewater reuse, and seawater desalination are considered in the model runs. Model runs were undertaken to simulate economically optimal water management for the year 2025 to address the challenges summarized in Table 1 using current management plans (base case) and diverse water management

Table 3
Description of water management portfolios optimized in Baja CALVIN.

	Description
A	Base case Current infrastructure with continued groundwater overdraft in Ensenada and Tijuana, but not in Mexicali. Colorado River–Tijuana aqueduct has a capacity of 5200 l/s. CRD has recommended environmental flows.
B	No overdraft with seawater desalination No overdraft is permitted. No expansion of the Colorado River–Tijuana aqueduct. The only new water source is seawater desalination. Las Arenitas wastewater treatment plant in Mexicali sends water to CRD.
C	Worst case Same as alternative B above but without desalination and other infrastructure changes, such as Colorado River–Tijuana aqueduct expansion.
D	Wastewater reuse Same as alternative A above, but with no groundwater overdraft and wastewater reuse in agriculture and aquifer recharge in Ensenada, and reuse for groundwater and surface water storage in Tijuana.
E	State aqueducts Ensenada receives its full allocation from the Colorado River (9 Mm^3/yr, 285 l/s) through a new aqueduct near El Carrizo Reservoir. An additional Mexicali–Tijuana aqueduct of roughly 120 Mm^3/yr (3800 l/s) is assumed.
F	Alternatives A + B + D Wastewater reuse, seawater desalination and expanded aqueduct Colorado River and Tijuana, new aqueduct to Ensenada but not additional aqueduct Mexicali–Tijuana.

portfolios (Table 3). For Tijuana–Rosarito, water management portfolios also follow recommendations from the Tijuana Master Plan (Camp, Dresser & McKee, Inc. [CDM], 2003). Residential water demand in year 2025 was estimated using population projections with constant per capita economic water demand. Agriculture was assumed to keep its current water use per hectare. Details for both urban and agricultural water demand estimations are presented in Medellin-Azuara et al. (2008b).

3. Results and discussion

One advantage of regional hydro-economic optimization models is the array of results for planning. Model results include optimized water allocations and operations, water scarcity, water scarcity costs, willingness to pay for additional water under scarcity conditions, economic value of facility expansions, operating costs and total water scarcity and operating costs. Additional results can be gained from post-processing (e.g., to find changes in cropping patterns, employment, regional economic impacts, etc.). Some results for this study are discussed with sensitivity analyses of conveyance capacity and seawater desalination costs.

3.1. Water management portfolios

Water deliveries, scarcity and costs for six water management portfolios are summarized in Table 4. The second column shows projected water demands for year 2025 in the urban and agricultural areas. The next two columns show optimized deliveries, and the difference between projected (target) demands and deliveries. The last three columns show annual values of scarcity costs, operating costs and total costs. In most cases, when the infrastructure and water is available, urban water demands are fulfilled. However, the Tijuana–Rosarito metropolitan is likely to have shortages.

In the base case (portfolio A, Table 3), overdraft for aquifers surrounding Ensenada and Tijuana–Rosarito is allowed in the model. Overdraft for Mexicali is not allowed as this aquifer is better monitored. For the 2025 base case, regional scarcity is 68 Mm^3/yr (scarcity cost $33.8 M/yr) of which Tijuana has a 21.4 Mm^3/yr shortage with an annual water scarcity cost of $32.7 million. Tijuana's severe scarcity raises the shadow value of water as high as $2.1/m^3 (not shown) due to conveyance capacity limits in the CRTA.

Table 4
Water deliveries, scarcity and scarcity costs for the main demand locations in Baja CALVIN (adapted from Medellin-Azuara et al., 2008b).

Water use	Delivery target (Mm^3)	Deliveries (Mm^3)	Scarcity (Mm^3)	Scarcity costs (US $M)	Operating costs (US $M)	Total costs (US $M)
Portfolio A: base case						
Urban	380	359	21	32.7		
Agricultural	1968	1921	47	1.2		
Total	2348	2280	68	33.8	282.6	316.4
Portfolio B: no overdraft with seawater desalination						
Urban	380	363	17	20.5		
Agricultural	1968	1931	38	3.7		
Total	2348	2293	55	24.2	284.5	308.7
Portfolio C: worst case						
Urban	380	320	60	425.2		
Agricultural	1968	1929	39	3.7		
Total	2348	2249	99	428.8	232.5	661.3
Portfolio D: wastewater reuse						
Urban	380	361	19	29.5		
Agricultural	1968	1957	11	0.4		
Total	2348	2318	30	30.0	261.9	291.9
Portfolio E: aqueducts						
Urban	380	375	5	6.3		
Agricultural	1968	1925	43	3.7		
Total	2348	2300	48	10.0	251.8	261.8[a]
Portfolios A + B + D						
Urban	380	365	15	17.5		
Agricultural	1968	1959	10	0.4		
Total	2348	2324	24	17.9	260.7	278.6[a]

[a] This total cost does not include capital cost of conveyance infrastructure expansions.

Agriculture in all locations would only be marginally affected as overdraft is allowed for Maneadero and Guadalupe. All urban locations but Tijuana–Rosarito receive their target water demands (second column in Table 4).

A base case without minimum instream flows for the Colorado River Delta (Medellin-Azuara et al., 2007) was also undertaken (not shown). Regional scarcity without dedicated environmental flows is 36 Mm^3/yr smaller; but regional scarcity costs decrease by less than one million dollars per year without expanding the CRTA. Dedicated environmental flows for the delta can have a relatively small annual cost. At a 5% discount rate, this annual scarcity cost in perpetuity has a present value of only $20 million dollars relative to a no minimum instream flows portfolio.

When overdraft is prohibited (portfolio B, Table 2), agriculture in Guadalupe and Maneadero are severely affected, as urban scarcity costs are higher and draw water from agriculture. Tijuana is unaffected by prohibiting further aquifer overdraft. When seawater desalination is available and overdraft prohibited (portfolio B, Table 2), Tijuana's urban water shortages are reduced only slightly.

For the worst case (portfolio C), no expansions of wastewater reclamation, desalination or conveyance capacity are undertaken and, in addition, groundwater overdraft is not allowed. Agricultural shortages in Mexicali are smaller than in base case (portfolio A), because the Colorado River aqueduct remains at its current capacity (4 m^3/s), and no water is devoted for the Colorado River Delta, more water remains for agriculture in the Mexicali Valley. Lack of infrastructure connecting east and west precludes an expanded market for water. An expanded water market would allow agricultural users in Mexicali to sell water to urban users in Tijuana. Idealized water markets in this work assume water can be transferred costlessly (after operation costs) among informed users and minimum government intervention. Willingness to pay for additional water in Tijuana is simply off-chart, and even Tecate suffers from lack of aqueduct capacity. Agriculture in Ensenada also suffers from continuing the *status quo*. Maneadero's irrigated agriculture virtually disappears and, without overdraft, Guadalupe meets only two-thirds of current water demands. Total scarcity costs are found by numerical integration of the shadow value or willingness to pay for additional water. Total scarcity costs for this alternative are more than twelve times those of the base case (portfolio A).

Wastewater reuse (portfolio D) provides some shortage relief compared to the *status quo* (portfolio A) for agriculture in Ensenada and Mexicali. With a non-overdraft policy, this option also reduces water scarcity in Tijuana–Rosarito. Yet, wastewater reuse does not fulfill demands in Tijuana due to high operation costs relative to water prices to consumers. The Colorado River Delta obtains the recommended inflows in this portfolio, using treated wastewater from Mexicali and agricultural drainage. By year 2050, water scarcity costs in this portfolio could be reduced by $25 million per year compared to the base case.

In portfolio E, two additional aqueducts (one for Tijuana and one for Ensenada) are included. This second aqueduct doubles CRTA capacity to 252 Mm^3/yr. More scarcity occurs for Mexicali, but with only a small economic cost. Agriculture in Ensenada takes little advantage of this conveyance expansion as operating costs are high. This portfolio reveals the potential economic gains of liberalized water markets for water for the Tijuana–Mexicali area. Idealized water markets imply negligible transactions costs for trading water, require minimum government intervention, and all water traders having perfect information. However, due to its high capital costs, a parallel and similar-sized Rio Colorado–Tijuana aqueduct is unlikely for several decades. Although total water scarcity is close to that in portfolio D, total scarcity costs decreases substantially because of much lower urban water scarcity.

In summary, the most promising water infrastructure portfolios combine reuse, expanded aqueducts and some seawater desalination capabilities (especially in Tijuana–Rosarito). To year 2025, a combination of these infrastructure changes yields the lowest operation and scarcity costs (last column of Table 4). Desalination alone compared with other water supply alternatives has lower total expected benefits. Total costs are still lower in portfolio E, as larger aqueducts significantly reduce water scarcity and water scarcity costs assuming operation costs are lower compared to other alternatives including desalination. However, high capital costs in portfolio E might make this alternative inferior.

3.2. Worthwhile infrastructure expansions

One feature of hydro-economic optimization models is that a form of sensitivity analysis is part of the results. Lagrange multipliers for storage and conveyance capacities provide information on how much total cost is reduced from infrastructure expansion.

The marginal economic value of expansion was analyzed for selected facilities in the Baja CALVIN network. These included the Colorado River–Tijuana aqueduct and the A. L. Rodriguez and El Carrizo reservoirs (Table 5). As more water supply options become available, the marginal economic value of expansions tends to decrease. Marginal economic value of facility expansions provide a measure of the likely system-wide cost reductions from increasing facility capacity by one unit. The Colorado River–Tijuana aqueduct seems to be the most economically promising expansion for northern Baja California. Scarcity in western Baja California is substantially reduced when water can be delivered from the east. However, when wastewater reuse is available for Tijuana–Rosarito, the economic value of CRTA expansion is cut in half. This highlights the potential of wastewater reuse to reduce regional water scarcity.

Expanding storage capacity in the A. L. Rodriguez and El Carrizo reservoirs provides small reductions in system-wide costs. Usually these reservoirs operate well below capacity, and floods are rare for Tijuana. At the A. L. Rodriguez reservoir, the flood control facility for Tijuana–Rosarito, average daily storage for 1995–2004 was 35 Mm^3 (35% of capacity), whereas El Carrizo was 28.3 Mm^3 (80% of capacity). Increased wastewater reuse increases the economic value of expanding both reservoirs slightly as one reuse option is to store reclaimed water in local reservoirs.

3.3. Sensitivity analysis

Another sensitivity analysis was done for conveyance capacity and desalination costs (Medellín-Azuara et al., 2008). Conveyance capacity through the aqueduct was selected since increasing the capacity of the CRTA has the highest marginal economic value of expansion. Seawater desalination cost was selected for the second set of sensitivity runs since this technology is part of current plans.

Fig. 3 shows the relationship between aqueduct capacity, water scarcity and water scarcity costs. Aqueduct capacity was increased from its current projected expansion 164 Mm^3/yr (5200 l/s) to

Table 5
Economic value of facility expansions in US $/1000 m^3 per year of expanded capacity (adapted from Medellin-Azuara et al., 2008b).

Facilities	Colorado River–Tijuana aqueduct	A. L. Rodriguez reservoir	El Carrizo reservoir
Base case	200	53	18
No overdraft and desalination	117	24	9
Reuse	109	33	14

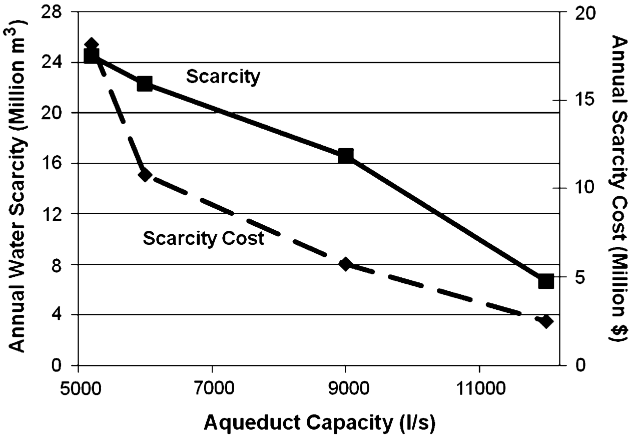

Fig. 3. Water scarcity and scarcity cost for Baja California in 2025 under optimized scenarios as a function of the Colorado River-Tijuana aqueduct capacity (adapted from Medellín-Azuara et al., 2008).

378 Mm^3/yr (12,000 l/s). Water scarcity declines at an increasing rate with aqueduct capacity, and water scarcity cost declines at a decreasing rate. At current operating and scarcity costs, the results in Table 4 show that economically effective management strategies might well include water conservation measures for Tijuana–Rosarito. This conclusion might change if economic values of water in Tijuana become high enough to offset current high costs of supply. Water scarcity costs rate of reduction changes depending on the aqueduct capacity. At lower aqueduct capacities (5200 l/s), more expensive water sources (such as seawater desalination) are used. A switch from more expensive sources to aqueduct use occurs with a slightly larger aqueduct. However, benefits from this expansion decrease as the more expensive sources are phased out early in the expansion. In hydro-economic optimization weighs supply costs against scarcity and plus operating costs. Higher supply costs make more water shortages economical. However, this may bring unintended adverse socioeconomic impacts for some groups.

Fig. 4 depicts use of seawater desalination and scarcity costs for a range of desalination costs from $0.8 to $1.5 dollars per cubic meter ($/$m^3$). Seawater desalination becomes promising water source for Tijuana–Rosarito when total costs drop below $1.1/$m^3$, including brine disposal, energy, capitalization and other major costs.

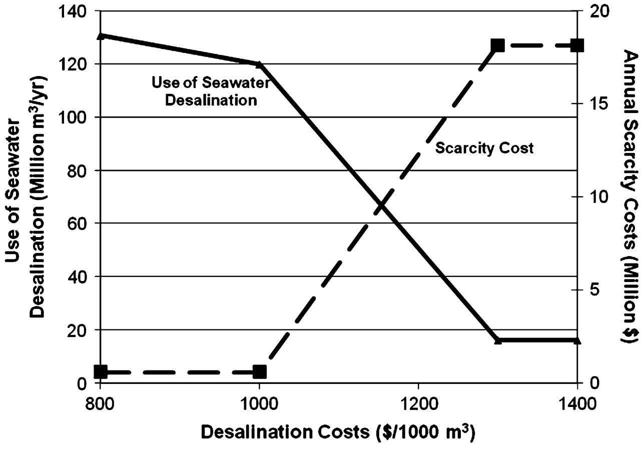

Fig. 4. Use of seawater desalination and water scarcity cost for Baja California in 2025 under optimized scenarios as a function of seawater desalination costs (adapted from Medellin-Azuara et al., 2008b).

For costs above $1.2/$m^3$, the use of seawater desalination in Tijuana–Rosarito is less than 20 Mm^3/yr (less than 10% of 2025 target demand in Tijuana). However, as costs drop below those of other options, use of seawater desalination increases. Scarcity costs increase dramatically when seawater desalination costs exceed $1.0/$m^3$. At current costs, seawater desalination is at a disadvantage compared to other water supply options in Baja California, such as a larger aqueduct or wastewater reuse. If seawater desalination costs decrease due to longer lasting membranes and reduced energy use (DWR, 2008), keeping energy and other costs roughly constant, this technology could become attractive and economical. However, increasing energy costs make this less likely. Government officials on both sides of the border are pursuing financing for binational seawater desalination facilities (SWRCB, 2005).

3.4. Model limitations

Limitations of CALVIN and Baja CALVIN have been discussed elsewhere (Draper et al., 2003; Medellin-Azuara et al., 2008b). Some additional limitations involve the lack of comprehensive hydrological studies at the time of this study, in particular for the Guadalupe aquifer. Groundwater overdraft may impose additional extraction, water quality and environmental costs not included here. While this region is unusual in that its operational hydrology is rather simple and stable, better information on interaction between surface and groundwater in Ensenada and Mexicali would be useful. However, hydrological variability is so small in this system that hydrologic foresight is probably not a major problem for this model. Furthermore, costs of particular water management options have some uncertainty. Institutional arrangements occur such that higher or lower water prices are charged depending on the purpose of use; agricultural water price is subsidized, residential and industrial prices have an increasing block rate structure in some cities. Water prices (rates) will influence shadow values and water scarcity costs. Water prices for urban use are for the average consumer, therefore scarcity cost might be underestimated (and scarcity over estimated) as higher end residential consumers are willing to pay more for water. Urban water demands for year 2025 follow current projections on population growth and *per capita* rates; however conservation may decrease these per capita urban demands. Agricultural demands are assumed able to forfeit water for urban uses, although market mechanisms might not be perfect. High transaction costs, institutional constraints and lack of connectivity between the water trading sectors may pose some challenges to the idealized water markets assumed in this paper. On the other hand, benefits of water use for each sector are not explicitly accounted in this model as the water scarcity cost merely provides the opportunity cost of water in alternative uses. Lastly, capital cost of alternatives may play a significant role for the tradeoffs involved in each portfolio; and therefore we attempted to represent existing plans for the region.

4. Conclusions

Hydro-economic models suggest promising portfolios for improving water management in integrated regional water resource systems. Here, a straightforward network flow formulation for northern Baja California, Mexico produced a wide range of insights which demonstrate the potential value of even highly simplified optimization models. Six policy insights arise from the Baja California modeling:

1. Baja California's agricultural, environmental and urban water users face large supply scarcities. Large economic losses will occur without water supply development and improved management.
2. Water markets increase flexibility and can buffer urban scarcity. However, future water market benefits for Tijuana–Rosarito are limited by current aqueduct capacity.
3. Economically promising investments include conveyance and wastewater reuse infrastructure. Expanding the aqueduct between Mexicali and Tijuana would greatly decrease water scarcity costs in Tijuana. For Ensenada, even at high conveyance costs, a new aqueduct connecting Ensenada to the Colorado River System would reduce the region's agricultural water scarcity.
4. For Ensenada and Tijuana–Rosarito, wastewater reuse along with other planned infrastructure expansions appears to be the most economically promising option. Optimized wastewater reuse might decrease overall costs by over $25 million per year in 2025.
5. Wastewater reuse is an economical source of environmental flows for the Mexicali Valley and the Colorado River Delta only if institutional arrangements exist for subsidized sale of this water, as no minimum flow requirements are currently enforced.
6. Seawater desalination is currently uneconomical for Baja California, relative to wastewater reuse, water conservation, water transfers and infrastructure expansion. Current urban water pricing for Tijuana–Rosarito makes seawater desalination less attractive than water rationing policies. Without conveyance infrastructure from the Mexicali Valley to Tijuana, seawater desalination can be economical with higher water prices, after some water conservation in Tijuana.
7. Given current institutional and political factors, and considering how water has traditionally been managed in the area, some solutions proposed by the model are less practical. For example an alternative aqueduct from east to west is unlikely because of its high capital costs. Likewise, large water transfers from the Mexicali Valley to urban uses may produce undesired distributional effects on the local economy. Nevertheless a simple network optimization formulation produced practical insights about regional water management infrastructure and policy.

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