The application of economic-engineering optimisation for water management in Ensenada, Baja California, Mexico

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Abstract Mathematical optimisation is used to integrate and economically evaluate wastewater reuse, desalination and other water management options for water supply in Ensenada, Baja California Mexico with future levels of population and water demand. The optimisation model (CALVIN) is used to explore and integrate water management alternatives such as water markets, reuse and seawater desalination, within physical capacity constraints and the region's water availability, minimising the sum of economic costs of water scarcity and operating costs within a region. The modelling approach integrates economic inputs from agricultural and urban water demand models with infrastructure and hydrological information, to identify an economically optimal water allocation between water users in Ensenada. Estimates of agricultural and urban economic water demands for year 2020 were used. The optimisation results indicate that wastewater reclamation and reuse for the city of Ensenada is the most economically promising alternative option to meet future water needs and make water imports less attractive. Seawater desalination and other options are not economically viable alone, but may have some utility if combined with other options for the Ensenada region.

Keywords Desalination; deterministic optimisation; wastewater reclamation; water management

Introduction

Baja California and California share many features, particularly a drought-prone climate and growing water demands. Traditional water supply planning and analysis methods were based on fixed water requirements and the concept of system water deliveries to always achieve these fixed requirements. Increased costs for providing 100% water supply reliability has led to more sophisticated views of water demands, moving to economic water scarcity, rather than requirements. Economic valuation has proved to be a simple, consistent and understandable principle to help evaluate complex integrated infrastructure and policy options to rationally balance increased water supplies, reduced water use and resource allocations, under hydrologic uncertainty (Jenkins *et al.*, 2003, 2004; Pulido-Velázquez *et al.*, 2004).

CALVIN (CALifornia Value Integrated Network) is an economic-engineering optimisation model that jointly considers water management and economic performance, including water sources, storage and agricultural, environmental and urban water uses (Draper *et al.*, 2003). CALVIN has been used successfully in California to explore water market behaviour and to facilitate economically driven managerial decisions. CALVIN results go beyond simple cost benefit analysis by taking into account the economic value of water for different users, water scarcity and supply costs. This information is then used to identify and develop economically promising combinations of water management activities including a broad array of options such as additional conveyance capacity,

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water reuse and desalination, deregulation, water markets and reductions in water use under different optimised scenarios.

The population of Northern Baja California has grown rapidly and water transfers and water marketing should begin to play a key role in major regional water plans. Ensenada, located 100 km south of Tijuana, relies entirely on groundwater as its potable water source. According to estimates made by the local water utility (CESPE), water demand can only be met in a sustainable manner until the end of 2006. Currently, Ensenada is one of the few cities in Mexico treating all of its wastewater. Although Ensenada's wastewater meets Mexican environmental standards for reuse, it is currently being discharged into the sea (Mendoza-Espinosa *et al.*, 2004). Besides urban water demand, two agricultural regions were included: Guadalupe and Maneadero. Guadalupe, is the most important wine producing region in Mexico. Maneadero is located 8 km south of Ensenada where a great variety of high value crops are produced, most of which are exported to the USA. In both cases, reclaimed wastewater could be used for irrigation as a substitute for groundwater. Alternatively, to meet Ensenada's future water demands, the National Water Commission (CNA) is considering seawater desalination and a new aqueduct to deliver water from the Colorado River. Both alternatives involve major capital investments and, for desalination, high operation costs.

This study employed economic analysis within an engineering optimisation framework to evaluate the promising use of these water management alternatives, independently and in combination, for the Ensenada region, within regional hydrologic and infrastructure constraints. Estimates of agricultural, residential and industrial economic water demands by year 2020 were used. Management alternatives included enhanced wastewater treatment facilities, reclaimed water conveyance infrastructure (for irrigation) and desalination capacity. The modelling approach, implemented using CALVIN, proved to be effective for identifying promising water management alternatives. Results show that wastewater reclamation and reuse is the most cost-effective alternative for meeting future water needs in the Ensenada region if groundwater overdraft is not an option. Furthermore, water imports either from Tijuana or from the proposed branch from the Colorado River aqueduct are less attractive when reuse is available. Seawater desalination is only a promising option when the cost of treatment is low and comparable to groundwater extraction.

Methods

Economic-engineering optimisation model

The study focused first on the quantitative understanding of the water resources situation in Ensenada. This quantification took place within the framework of a computer model, called CALVIN that offers a systematic approach to study such complex water resource management problems. CALVIN model 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 (Tanaka *et al.*, 2003; Jenkins *et al.*, 2004; Pulido-Velázquez *et al.*, 2004). More recent applications of the model include the potential effects of climate change on California water management (Tanaka *et al.*, in press).

A region in CALVIN is represented as a system of nodes and links (Figure 1). Nodes include reservoirs, aquifers, agricultural region, urban centres, water treatment facilities and pumping stations. Links are physical connections between two nodes and may have associated costs or gains/losses associated with water flows. Links can also be restricted to a maximum flow such as a conveyance capacity or a minimum environmental or mandated flow. The model is a network flow optimisation model which integrates an

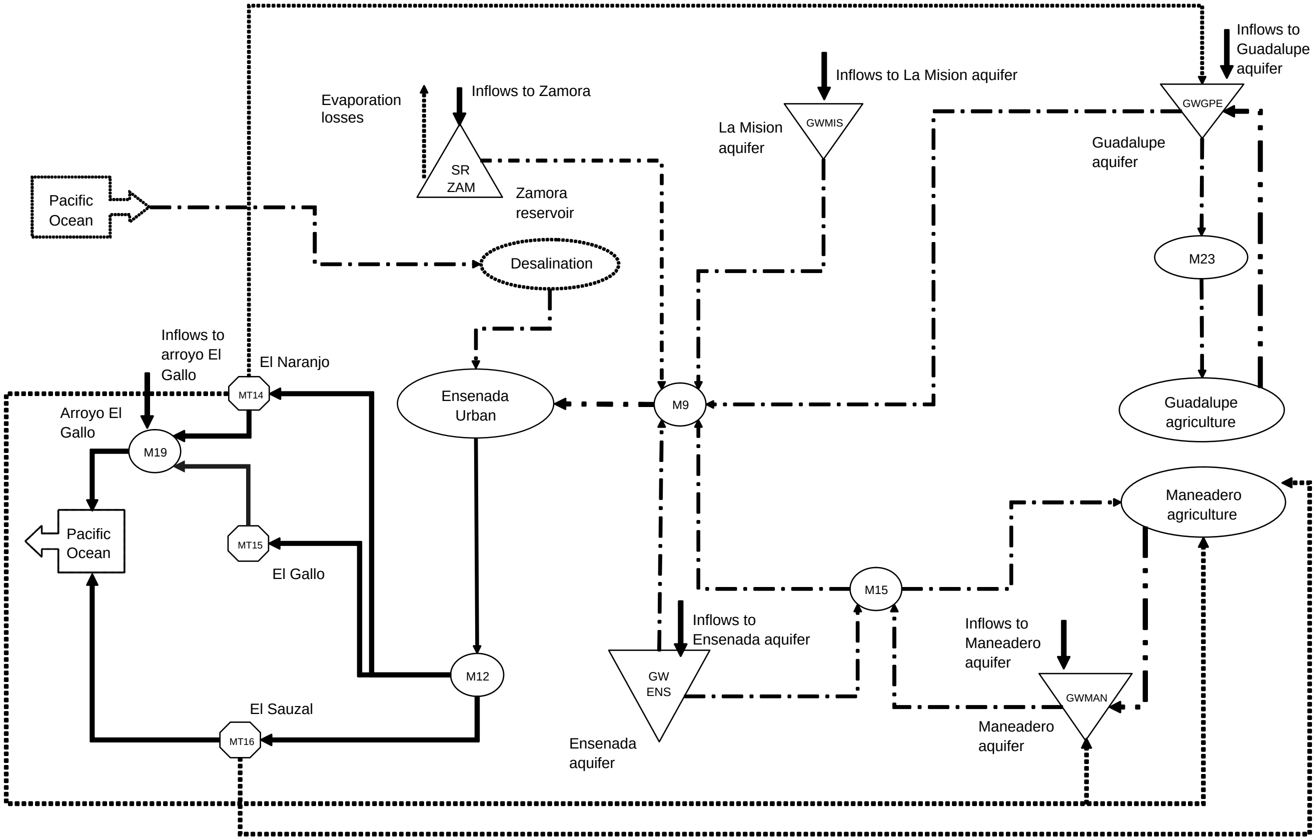

Figure 1 General schematics of the CALVIN model for the Ensenada region

engineering description of a water management system, economic descriptions of water use demands and its costs, and specific environmental and water allocation policies to identify promising solutions to regional water resource problems (Draper *et al.*, 2003). The network flow optimisation problem is solved using the HEC-PRM optimisation software developed by the US Army Corps of Engineers.

This software seeks water operations and allocation decisions which minimise the total cost of operation in a system (the sum of operating costs and water scarcity costs in urban and agricultural demand areas). In minimising this total cost, the water management decisions are limited by hydrologic, infrastructure and institutional constraints. The objective function is to minimise overall system costs over the entire modelled time period, represented mathematically by:

$$\text{Min}\, Z = \sum_i \sum_h c_{ij} X_{ij} \tag{1}$$

where Z: total cost; c_{ij}, cost coefficient; and X_{ij}, flow from node i to node j *(arc ij)*.

In this formulation, each node represents a location in time and space. Constraints in CALVIN include maximum and minimum flow limits and conservation of overall mass (Jenkins *et al.*, 2001). These constraints represent the physical and institutional bounds on water operations and allocations. Mathematically, constraints can be represented as:

$$\text{mass conservation} \quad \sum_i X_{ji} = \sum_i a_{ij} X_{ij} + b_j, \qquad \text{for all nodes } j; \tag{2}$$

$$\text{a maximum flow} \quad X_{ij} \le u_{ij}, \qquad \text{for all arcs;} \tag{3}$$

$$\text{a minimum flow} \quad X_{ij} \ge l_{ij} \qquad \text{for all arcs;} \tag{4}$$

where b_j are external inflows to node j; a_{ij}, gains or losses on flows in arc; u_{ij}, upper bound on arc; and l_{ij}, lower bound on arc.

Results from optimisation using CALVIN are not limited to flows between nodes and storage levels in reservoirs for every time step modelled. The combined use of an economic objective function with a mathematical optimisation algorithm provides, for each location and time step, the marginal economic willingness to pay of users for additional water (the Lagrange multiplier for constraint 2). Similarly, the economic value of a unit expansion of infrastructure capacity is estimated by the Lagrange multiplier for u_{ij} in equation (3), for each arc and time step. The economic value of environmental uses or previously allocated by government mandates is not valued directly in CALVIN. Instead, these water uses are represented as minimum flows in equation (4), and their economic opportunity costs for other water users are evaluated with the Lagrange multiplier on this constraint.

Scenarios in CALVIN are created by modifying the parameters in equations (1–4) above. An aqueduct expansion would increase the upper bound u_{ij} for that particular link. It is also possible to prevent overdraft of aquifers by establishing an end-of- period storage. Operation costs are included in the c_{ij} parameter of equation (1), thus having water flowing from a desalination facility may have unit cost, as would flow from an artificial recharge facility.

The modelling alternatives examined in this paper represent the following water management options at year 2020 water demand levels:

1. Current operating and allocation policies, referred to as *status quo;*
2. Seawater desalination as a new source of potable water;
3. Wastewater reuse for aquifer recharge and irrigation; and
4. Combined seawater desalination and wastewater reuse.

The *status quo* would continue to provide water at projected 2020 levels to the city and the agriculture in Guadalupe and Maneadero. Yet, expansion in conveyance capacity and water treatment would have to occur for the urban sector. It is assumed that water demands for the city of Ensenada will increase from its current 22 million cubic meters per year (Mm^3/y) to 39.5. Mm^3/y (CNA, 2005). Agricultural water demand is assumed to be constant. Furthermore, it is assumed aquifer overdraft would continue to be allowed.

Seawater desalination has been advocated as an alternative water supply (CNA, 2004). In this study a new desalination plant with a capacity of 12.6 Mm^3/y for the city of Ensenada is considered. Two cost levels (low and high) for seawater desalination were used. The low price mimics current CESPE costs for groundwater delivered to the city. High water desalination costs in this study where established at 1.6 US dollars per cubic meter.

The city has three wastewater treatment plants: El Sauzal, El Gallo and El Naranjo. All plants use activated sludge as treatment processes and the effluents are disinfected with chlorine before being discharged to local creeks that eventually reach the ocean. The effluent from El Naranjo could be used for the irrigation and/or aquifer recharge in the agricultural valley of Maneadero (Mendoza-Espinosa *et al.*, 2004). Effluents from El Gallo and El Sauzal comply entirely with Mexican legislation related to the reuse of wastewater for activities where the public is in direct and indirect contact with the wastewater. With some additional conveyance capacity, the reclaimed water could be used for crop irrigation or recharge of the Guadalupe Valley aquifer (Mendoza-Espinosa *et al.*, 2005).

For wastewater reuse, four new projects were considered (see Figure 1):

1. Up to 9.4 Mm^3/y of artificial recharge of the Maneadero aquifer using treated wastewater from El Naranjo wastewater treatment plant.
2. Up to 6.3 Mm^3/y of artificial recharge of the Guadalupe aquifer using treated wastewater from either El Naranjo or El Gallo wastewater treatment plants.
3. Up to 9.4 Mm^3/y of treated wastewater from El Naranjo wastewater treatment plant for irrigation in Maneadero.
4. Up to 6.3 Mm^3/y of treated water from El Sauzal for irrigation in the Guadalupe Valley.

Finally, seawater desalination and the preceding wastewater reuse option were combined into a last water management alternative for Ensenada. Only variable costs were considered for all water management options. Desalinated seawater was restricted to be used solely for urban consumption, whereas recycled wastewater could be used for irrigation and groundwater recharge.

Data requirements

The CALVIN Ensenada regional model required gathering a great amount of information for the model database. The schematic is presented in Figure 1. The model included four aquifers that supply water to the city of Ensenada, one reservoir (Zamora), two aqueducts, several pumping stations, three wastewater treatment plants, one urban demand and two agricultural demands (Maneadero and Guadalupe).

Data for the present study comes from the National Water Commission (CNA) databases, the local utility company (CESPE) and interviews with local farmers. Monthly hydrologic data from 1983 to 1993 were collected to estimate inflows to the aquifers.

The city of Ensenada receives water from four aquifers (Ensenada, La Mision, Guadalupe and Maneadero) and a reservoir (Zamora). Estimates of storage capacity, water extractions, evaporation rates and natural recharge were made using data from CNA. CESPE provided information on potable water and wastewater treatment capacities and costs, conveyance capacity, pumping costs, water tariffs and existing physical connections between network elements.

Agricultural production costs were estimated using local farmer's reports on the region's crops, planted area, crop yield, water use, labour use per crop, wages, off-farm labour opportunities, pumping costs and historical institutional rules. A microeconomic agricultural production model was used to derive economic water demands for irrigation water.

Urban scarcity costs were calculated with water demand projections for 2020 obtained using population growth estimations from SAPROF (1999). Following Jenkins *et al.* (2001), water scarcity value for urban demand nodes was obtained. A constant (-0.2) price-elasticity of demand for urban water was assumed. Observed water consumption and prices, and a constant *per capita* consumption rate were used to derive year 2020 economic water demands.

The collected data were incorporated into a database for input to the optimisation solver, which uses a generalised network flow optimisation algorithm to find the set of water operations and allocations for maximising regional economic net benefits (minimising net costs).

Results and discussion

Results of this study indicate that flexible and integrated water management schemes can reduce the probability of water shortages and overall costs. Currently, all four aquifers are being overdrafted, yet water reuse may reduce dependence on groundwater. Model runs in this study allow overdraft at current rates.

In addition, overall results from this study show that water reuse is a superior water management option compared to low-cost seawater desalination and the *status quo*. Table 1 shows a breakdown of water use in the Ensenada region by source. As an expensive source, desalted seawater would be used only in the city of Ensenada (column 2 Table 1). When both water reuse and desalination are available, the use of desalted water drops by 8.2 per cent points (column 4).

Other findings include:

1. The *status quo* is unsustainable. Expansions in conveyance capacity are needed to meet future demands even if overdraft of aquifers is allowed. Therefore, either new sources of water or measures to limit groundwater extraction are needed. Continuing to overdraft aquifers such as Maneadero will increase saline intrusion and jeopardise

Table 1 Water supply share by source

Supply	Options considered (share in per cent)			
	Current policy	**Low cost desalination**	**Water reuse**	**Reuse and LC desalination**
Urban				
Groundwater	97.0	72.3	97.0	80.5
Surface	3.0	3.0	3.0	3.0
Desalinated	0.0	24.7	0.0	16.5
Recycled	0.0	0.0	0.0	0.0
Sum	*100.0*	*100.0*	*100.0*	*100.0*
Agricultural				
Groundwater	100.0	100.0	77.7	77.7
Surface	0.0	0.0	0.0	0.0
Desalinated	0.0	0.0	0.0	0.0
Recycled	0.0	0.0	22.3	22.3
Sum	*100.0*	*100.0*	*100.0*	*100.0*

its long-term availability as a water source for both agricultural and urban uses (Daesslé *et al.*, 2005). Wastewater treatment facility expansions will be needed to accommodate increases in wastewater generation. If no action is taken, a compromise between the agricultural use and the urban use of water will have to be made. Current tendency seems to be in favour of urban growth thus, the agricultural sector would shrink significantly, as water sources currently used for agriculture are shifted to urban uses with higher economic values.

2. Low-cost seawater desalination is a better water management option compared to the *status quo*, since willingness to pay for *imported* water is reduced (Table 2). (Willingness to pay in the context of this study means how much a user would pay for one additional unit of water). Nevertheless, this would be the case only if the cost of desalinated water compares favorably to current water production costs using groundwater. High seawater desalination costs were never used in these model runs. Currently, most water utilities in Mexico are state owned and operate at zero profit level. Therefore, investment on research and development of new technologies is not pursued and the water utilities rely mostly on water tariffs. High cost desalted seawater may only exacerbate financial issues, since a strong increment in the water tariff may encounter strong social and political opposition.
3. Wastewater reuse on its own can reduce shortages and willingness to pay for imported water from the Colorado River system (In this context, imported water means water that has to be brought from a separate region). By increasing local supplies of water, local wastewater reuse for irrigation or aquifer recharge would greatly reduce the costs of water scarcity, leaving a much smaller amount of local water scarcity to be accommodated by water allocation, water conservation, and increased water use efficiency. In this case, increased wastewater reuse would reduce the value of imported water by 57%, avoiding considerable capital and operating costs for such a new supply. If the required wastewater reuse infrastructure is built, seawater desalination may not be cost-effective. Table 2 shows that the willingness to pay for this imported water decreases as seawater desalination and wastewater reuse options are available.

At current extraction and water consumption levels in Ensenada, new water sources would have to be found to keep up with water demand projections. Therefore, there is an inherent willingness to pay for imported water to avoid shortages. Table 2 shows that desalination alone would lead to little reduction in the value of imported water. However, wastewater reuse alone and wastewater reuse combined with desalination would reduce substantially both water scarcity costs and the value of additional water imports.

All models have limitations and this is not less true for CALVIN. Main limitations are data quality, system simplifications and a non-exhaustive economic representation (see Jenkins *et al.*, 2004). In particular, 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 decisions.

Nevertheless, having this type of analytical tool for Baja California allows more definitive answers to many water and environmental issues for this region. Precise

Table 2 Reduction in economic value of imported water

	Options considered (percent with respect to current policy)		
	Desalination (low cost)	Wastewater reuse	Wastewater reuse and desalination (low cost)
Reduction in economic value of imported water	1.4%	15.8%	16.1%

applications of optimisation insights will require further testing and refinement by more detailed simulation studies. Further work will also link a larger model of Baja California, Mexico to an existing California model to allow a better quantitative exploration of cross-border water management issues.

Conclusions

This study demonstrates that economic-engineering optimisation can provide insights regarding the best combination of water technology applications and the potential of newer water management practices, such as wastewater reuse over older practices such as increased water imports. Traditional water management and planning can prescribe excessive expansions of supply by considering only supply costs and not the economic costs of water scarcity. Optimisation methods, such as those demonstrated here, also provide a rational engineering basis for design of a mixed portfolio of water supply actions for future conditions. With growing water demands for Ensenada, Mexico, new water sources would be needed in the near future. Wastewater reclamation and reuse for the city of Ensenada is potentially the most economically promising option for guaranteeing a reliable and economical supply of water to the city. Seawater desalination alone appears economically inferior and would need to be combined with other management activities, including wastewater reuse, to become more economical.

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