Economic-Engineering Analysis of Water Management for Restoring the Colorado River Delta

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Abstract

This dissertation offers an economic-engineering systems analysis of environmental water flows to the Colorado River Delta (CRD). Systems analysis provides a framework to integrate hydrology, competing water demands, and hydraulic infrastructure as well as institutional policies and physical constraints in a regional water allocation model. Environmental water uses are often included in hydro-economic models via minimum flow restrictions. In this study, a systems analysis tool based on the CALVIN model is developed to incorporate minimum environmental water flow restrictions within a hydro-economic representation of the CRD region of Mexico. Shadow values of the environmental flows from this model estimate opportunity costs of competing water uses, including agricultural and urban.

Agricultural and urban water demand models are used to obtain water shadow values by use. The agricultural demand model was developed deductively using positive mathematical programming. Shadow values for urban uses under block rate pricing structures were obtained using econometric analysis. For policy analysis, different levels of minimum flows are analyzed. Sources of water include idealized water markets in the CRD, water imports, infrastructure changes and wastewater reuse.

Results show that designated environmental water flows are likely to have greater impacts on agricultural than urban uses. Mandated flow regimes and liberalized markets for water appear to be promising strategies among policy alternatives to restore and maintain ecosystem functions in the CRD. For the policy scenarios simulated, no significant scarcity cost reductions arise from additional hydraulic infrastructure. Furthermore, shadow values of environmental flows can be so small that interboundary water transfers from the United States hold little promise for restoration. Findings highlight the importance of working out institutional constraints and suggest ways to take water management alternatives from the modeling laboratory into the real world. Systems analysis and the CALVIN model are useful screening tools that can provide policymakers quickly and effectively with information on policy alternatives, while integrating knowledge about diverse aspects of water availability and use in a region.

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1.1 Introduction

Water for environmental purposes is a longstanding issue in many parts of the world. Offstream uses such as urban and agricultural often have first priority in water allocation, for legal and economic reasons. A vast effort has been made in the literature to economically value instream uses of water as an environmental public good (Young 2005). Common valuation techniques for environmental water use include revealed preference and expressed preference methods. Less frequently, water for environmental purposes has been valued in terms of opportunity cost of alternative uses.

The main purpose of this dissertation is to contribute to the existing literature on valuation of water uses and application of systems analysis for habitat restoration in the Colorado River Delta. Agricultural water use values are developed using application of positive mathematical programming using a more flexible production function at a spatially-disaggregated level. Urban water use values are developed using more empirical econometric methods for a block rate structure using aggregated data. These water use valuations were employed in an economic-engineering optimization model of the Mexicali Valley region, which also represents water availability, infrastructure, and water management decisions. An application of the model suggests promising water management alternatives for conservation and traditional consumptive uses under different environmental flow policies.

This research estimates the regional economic cost of environmental flows using an economic-engineering optimization model driven by minimizing water scarcity costs for urban and agricultural uses, within infrastructure, hydrologic, regulatory, and environmental constraints. Economic scarcity costs for modeled urban and agricultural water deliveries are obtained from spatially distributed water demand curves. The marginal economic costs of environmental water use are given by the Lagrange multipliers on minimum environmental flow constraints. Valuation of environmental flows can be established by decision-makers selecting their preferred location along the trade-off curve of environmental flows and economic cost. The Colorado River Delta in Mexico (CRD) is used as a case study.

In subsequent sections, a literature review on environmental water valuation is offered. An introduction of the general modeling approach in this dissertation follows this literature review. In the last section, the CRD is presented as the selected study site.

1.2 Literature Survey

The literature on valuing water for environmental uses is developed mostly for recreation and aesthetic purposes. Usually, values obtained for water are for a particular recreation activity or site (Gibbons 1986). Direct market data on willingness to pay or prices for environmental uses are almost inexistent. With these limitations, alternative valuation techniques have been developed to estimate willingness to pay for environmental uses.

Some considerations in valuing water for environmental purposes include hydrological and climatic conditions, seasonality, institutional arrangements and infrastructure. Hydrological and climatic conditions are characterized by uncertainty, and a reasonable effort can be made to account for it in eliciting economically optimal environmental water assignation and acquisitions (*e.g.* Hollinshead and Lund 2006). Literature has also addressed institutional arrangements such as water markets, and promising changes in hydraulic infrastructure (Vaux and Howitt 1984, Lund and Israel 1995).

Young (2005) identifies at least four broad valuation techniques for water as an environmental public goods. Valuation methods are grouped into revealed preference, expressed preference, benefit transfer and meta-analysis. The first two are the most common in literature. Revealed preference techniques indirectly estimate value by using field data on actual environmentally-related decisions made by actual consumers. Expressed preference methods 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 valuation studies to a different location and conditions. In meta-analysis a statistical analysis is performed to previous research estimates. Results are aimed to explain differences in estimates across studies within the meta-analysis. Results provide initial information for benefit transfer (Young 2005).

In his literature review, Loomis (1998) argues that the opportunity cost for traditional uses of minimum instream flows often is below actual willingness to pay for them for recreation and habitat conservation uses. His literature survey includes methods such as contingent valuation and travel costs, which according to others (*e.g.* Carson *et al.* 1996), do not show no significant difference in currency value for quasi-public goods. Using contingent valuation, Daubert and Young (1981) found that water's marginal value in recreation may exceed that for agriculture, under some conditions. However, Yardas *et al.* (1982), found travel cost methods perform better for minor non-user value when single-trips are pervasive (Gibbons 1986). A challenge to this method is that attributes of the study site other than water have to be isolated. Other challenges to travel cost methods are the definition of the denominator in the units of the valuation, and that this valuation is average and not marginal (Gibbons 1986). Thus comparisons and results of these two main stream approaches remain controversial (Shabman and Stephenson 2000).

Despite their limitations, results from travel cost and/or contingent valuation methods are *the standard* for non-market water valuation in the economic literature. Furthermore, results from contingent valuation and travel costs have been used as inputs for regional water management models (Loomis *et al.* 1986). These models are usually optimization models, in which water is allocated to maximize overall benefits (Diaz and Brown), or to minimize operating and scarcity costs (Jenkins *et al.* 2004). For example, mathematical programming has been used to evaluate the gains from trade of using market mechanisms versus additional conveyance and storage infrastructure. Vaux and Howitt (1984) using water demand projections for year 2020, estimated that larger social benefits are obtained from more liberalized markets than from additional investments in infrastructural water resources projects.

One of the first attempts to quantify opportunity cost of water transfers considering minimum flows was Booker and Young (1994) on the Colorado River. Although these minimum flows were mandated deliveries to Mexico by the 1944 Water Treaty and not environmental flows, the modeling approach is close to the one proposed by this study. These authors used a basin optimization model under different schemes of interstate water transfers with a mean annual flow in the Colorado River of 16 billion cubic meters per year. Water quantity and quality were endogenous in their model. Their study used benefit functions for agricultural water, hydropower and urban uses, with the overall objective of maximizing benefits across users under different institutional restrictions to evaluate gains from trade under different institutional schemes of water allocation. One of their most valuable conclusions is that interstate water markets of traditional consumptive uses alone would not efficiently allocate water resources from the Colorado River Basin (p. 84). Exclusion of non-consumptive uses reduces the potential gains from the *laissez-faire* scenario. Nevertheless, liberalized interstate markets alone generate about 64% of the total possible gains under optimized water allocation. Other gains arise from hydropower and salinity control actions.

Economically optimal water allocation of environmental uses has been also addressed by Ward (1987). Using the Wild River Basin in New Mexico as a case study and the travel cost method to estimate recreation water demand curves, the author concluded environmental uses can be compared to traditional consumptive uses in the basin. In his model, Ward maximizes yearly value of instream recreation benefits using a dynamic formulation. His results provide shadow prices as the “willingness to pay for instream use net of other values forgone in the basin for one more” volumetric unit of water (p. 390). One limitation of the model by Ward is that forgone water opportunity cost is fixed at a certain “market price” for all uses.

A more recent application involving optimization and contingent valuation for environmental flows for fish was performed by Hickey and Diaz (1999) using the optimization model AQUARIUS (Diaz and Brown 1997). The empirical application was aimed to elicit water allocation strategies that enhance and/or improve habitat for some fish populations. They concluded an instream flow program should be in place for the Cache La Poudre River. However willingness to pay for water in recreational fisheries did not outbid the water *rental market* for agricultural use of the study case.

When available, estimates of the value of instream water uses such as hydropower, fish habitat or recreation, often can compete economically with offstream uses. However, when instream water use values are unavailable, optimization models offer guidance for meeting traditional offstream demands within flow restrictions for environmental and other uses.

If cost minimization is the objective of the optimization model, the value of water devoted to the environment can be used as a proxy for the shadow value on the minimum flow restriction in the program, which is the core of this dissertation. Under this modality is the dual of a benefit maximization program, and as such, the shadow value of water is provided from the supply side and not in the demand side as occurs with non-market valuation techniques described above. Shadow values are opportunity costs to other uses of water in a system. If environmental flow requirements are set knowledgeably and rationally, the marginal environmental value of these flows should equal their marginal opportunity costs to other water users. On the demand side, the optimization program requires benefit functions as opposed to cost functions. In this case, a social optima is attained when the marginal benefit of consumptive uses, net of habitat loss and degraded water quality externalities equals marginal benefits of environmental water flows. Nevertheless, it is out of the scope of this dissertation to provide welfare measures such as the consumer surplus of environmental water uses.

1.3 Modeling Approach

This research uses systems analysis to estimate value of environmental water uses as an opportunity cost to other uses. A lower bound estimate of the willingness to pay from reductions by urban and agricultural users for water devoted to the environment is obtained as the Lagrange multiplier on a minimum water inflow constraint in a watershed. This modeling lies within the framework of a large-scale optimization model called CALVIN for CALifornia Value Integrated Network (Jenkins *et al.* 2001, Jenkins *et al.* 2004). Applications of CALVIN in California include the economic values of conjunctive use (Pulido-Velazquez *et al.* 2004), impacts of dam removal in the Hetch Hetchy system (Null and Lund 2006), and long-term climate change (Tanaka *et al.* 2006).

System model results from CALVIN (right hand of Figure 1-1) are used to establish a framework for revealed preference estimates of the economic value of environmental flows. Three alternative water uses exist within a complex hydraulic network namely, agriculture, environment and urban. Water value is fundamentally based on agricultural and urban uses.

Total economic costs for the system are the sum of scarcity costs for agricultural and urban uses plus operating costs (pumping, treatment, etc.) for a region. Water is assumed to be a scarce resource for the three users. The opportunity cost of dedicating water flows for environmental uses rather than making these flows available for the other two users is the value of the shadow costs (Lagrange multipliers) on the environmental flow constraints in the system model. Marginal valuation of environmental flows is then implied by the society's selection of a point of operation on the trade-off curve between environmental flows and other economic performance.

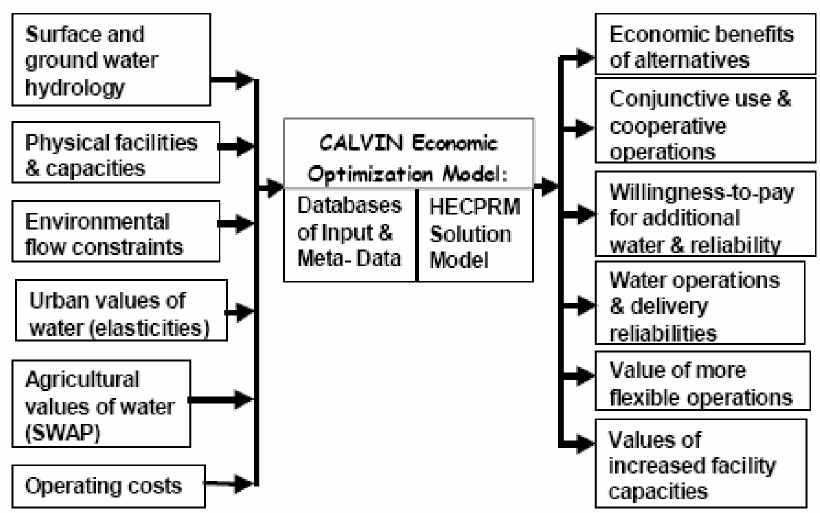

Figure 1-1 Data flow in CALVIN (after Jenkins *et al.* 2001).

This approach differs from mainstream contingent valuation and travel cost method techniques. Shabman and Stephenson (2000) extensively review the economic literature on shortcomings associated with the aforementioned methods. In this study, willingness to pay for environmental water is a by-product of a larger user-interrelated water resources network for the northern Baja California region using CALVIN. One advantage of this approach is that associated opportunity costs of alternative uses of water and operation costs are explicitly considered.

Although water quantity and/or minimum environmental flows are common attributes, water quality is also a salient issue for the CRD. Low flow regimes have been associated with degraded water quality and habitat for birds and other species in the CRD (Garcia-Hernandez *et al.* 2001). However, this consideration is beyond the scope of this research. Two applications of water demand and water quality in the Colorado River include Booker and Young (1994) and Lee *et al.* (1993). For the Colorado River Delta in Mexico, water quality is more suitable for a bi-national study, since most water quality management is at this larger scale. Thus the opportunity cost of environmental flows estimated in this study could be viewed as a lower bound of the marginal willingness to pay for improved water quality.

1.4 Case Study

The Colorado River Delta in Mexico is located in the northeastern part of Baja California, Mexico surrounded by the prominent Irrigation District 014 and the border cities of Mexicali, and San Luis Rio Colorado, Sonora. This region flourished in the early 1900's as American corporations such as the Colorado River Land Company and the California Development Company, established and developed agriculture and irrigation infrastructure and in the Mexicali Valley.

Water Statistics from the National Water Commission (CNA 2004) show that Mexicali historic (1941-2000) average rainfall is 54.2 mm. Maximum temperature has been as high as 54.3° C. In the midst of the Valley, where agricultural activities take place, has more extreme temperatures with a record of 57.0 °C and annual average rainfall of 33 mm (Sánchez-Munguía 2004). With such an arid and dry environment, agriculture in the Mexicali Valley is essentially all irrigated.

1.4.1 Institutional Background

National Water Law (NWL) governs water resources management for Mexico. The National Water Commission (CNA) was established in 1989 as part of the Agriculture and Hydraulic Resources Secretariat (SARH). The CNA is now part of the Ministry of Environment (SEMARNAT). The CNA has ultimate authority to administer water resources nationwide. Water users, including municipal water utilities and farmers, receive water use rights granted from CNA in the form of concessions. Users that benefit from a concession are listed in the National Public Registry of the Water Rights (RPDA for the Spanish Acronym), created as a result of the 1992 NWL. Furthermore, NWL set the basis for establishing markets for water use rights. In the Mexicali Valley water markets are more developed than elsewhere in Mexico (Kloezen 1998). The CNA encourages water transfers within local water district modules but taking water outside the basin is not allowed.

Water users are organized at four levels. The first level is the module (*módulo*), legally constituted as a civil association. The next higher level of authority within a district is the *hydraulic committee* which can be established with user members for an irrigation district. Also at the district level is possible for a user to join a *Sociedad de Responsabilidad Limitada* (SRL), which is mostly concerned with day to day operation at a higher hierarchical level than the module. Nationwide, users can affiliate to a National Association of Irrigation Users (ANUR, for the acronym in Spanish), although this association is more a forum than an legally empowered organization (Gorriz *et al.* 1995).

CNA typically does not guarantee a lower bound of water to users within the modules. Nonetheless, Irrigation District 014 is a special case since water from the 1944 Water Treaty sets this lower bound. For decades, the institution in charge of scheduling water deliveries has known well in advance the water availability for the district. Operational releases or exceedences from the US are not counted toward the Treaty quota, although they are used for irrigation, groundwater recharge or ecological use. One shortcoming of the existing Mexicali Valley infrastructure is that water cannot be stored outside of the current hydraulic network. Thus if water is not used for anthropogenic activities, it will essentially go to groundwater recharge, ecological use or ultimately evaporation losses.

Before the National Water Law of 1992, irrigation districts in Mexico were operated and maintained by the National Water Commission. By the end of 1994, about 2.5 million hectares within 55 irrigation districts nation-wide had been transferred to water user associations (Gorriz *et al.* 1995). With this reform, water user associations (WUA) are responsible for operation and maintenance (O&M) of irrigation infrastructure. This program apparently has increased water fees to farmers but also the level self-sufficiency for maintaining and operating irrigation infrastructure. Gorriz *et al.* (1995) reported that irrigation districts in the northwest region of Mexico had reached 90% of self-sufficiency.

Outstanding O&M expenditures are financed by CNA. Nevertheless, Irrigation District 014 records suggest self-sufficiency at that time was roughly 60% (CNA 2005).

1.4.2 Water Sources

While water might seem scant for agriculture in this zone, the Mexicali Valley is unique in Mexico in having a very reliable lower bound for water availability. The 1944 US-Mexico Water Treaty provides the valley with at least 1,850 million cubic meters (MCM) per year. The other two sources of water are the Mexicali Aquifer and the *Mesa Arenosa de San Luis Río Colorado* Aquifer. The first is the largest aquifer in the country with an annual availability of 700 MCM. The Mexicali Aquifer has 658 wells of which 422 are private. The Mesa Arenosa aquifer on the other hand, is strictly controlled to yield 197 MCM/year, with a battery of 67 federal wells (Sánchez-Munguía 2004). Water rights on the Mesa Arenosa aquifer are intended for urban use in the northern border cities of SLRC, Mexicali, Tijuana, Tecate and even Ensenada.

A breakdown of water sources and allocation is shown in Figure 1-2. The water assigned to all five cities is 197,358 thousand cubic meters per year. Most of it (82%) goes to the large cities of Mexicali via de *Independencia* Canal and to Tijuana and Tecate, through the *Reforma* canal and then through the Colorado River-Tijuana aqueduct. The Mesa Arenosa groundwater has been assigned for urban use mostly west of the Colorado River (with the exception of SLRC). Nevertheless, for operational efficiency the cities at the west are supplied by the surface irrigation network, whereas SLRC and irrigation east of the river use the Mesa Arenosa water. Inflows from Arizona are estimated to be 100 MCM per year (Sánchez-Munguía 2004).

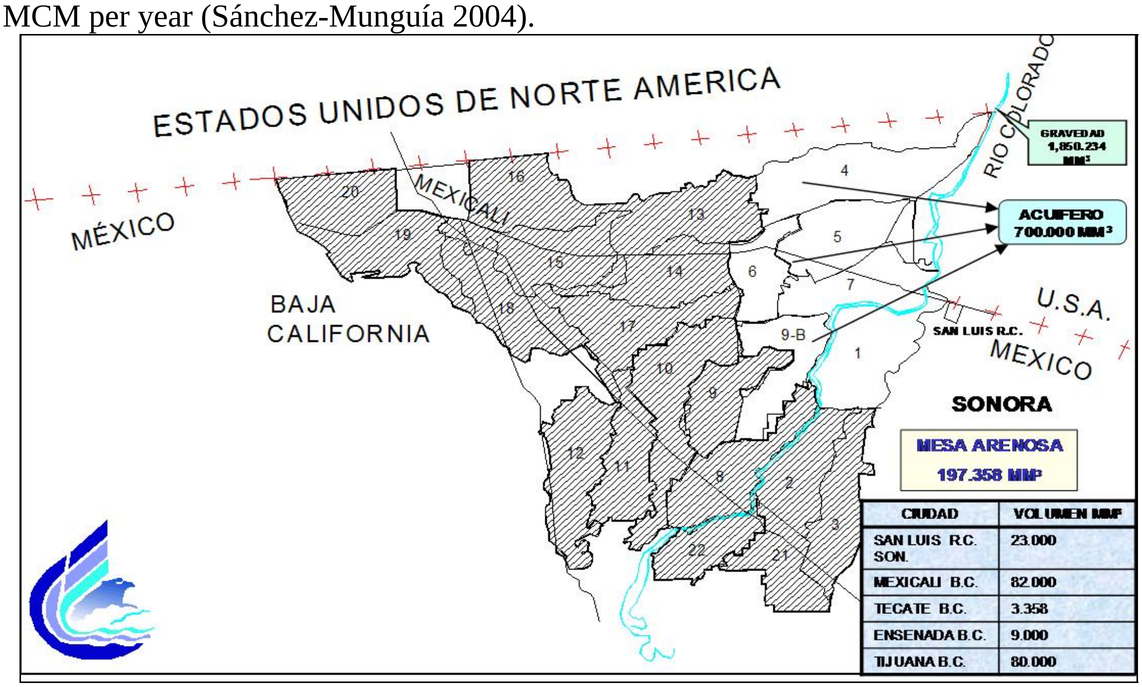

Figure 1-2 Water Availability in Irrigation District 014 (Source: CNA D.R. 014).

1.4.3 Ecosystems in the Colorado River Delta

The Mexican portion of the CRD (Figure 1-3) occupies more than 180,000 hectares, which is only 10% of the Delta's area prior to upstream water development that began in the early 1900s in the US and Mexico (Glenn *et al.* 2001). The Colorado River is the main source of water 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, deterioration of water quality, and abetted 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 is protected as part of the Biosphere Reserve of the Gulf of California since 1993. Nevertheless, severe droughts, increasing agricultural and urban demands and institutional constraints are challenges for CRD restoration.

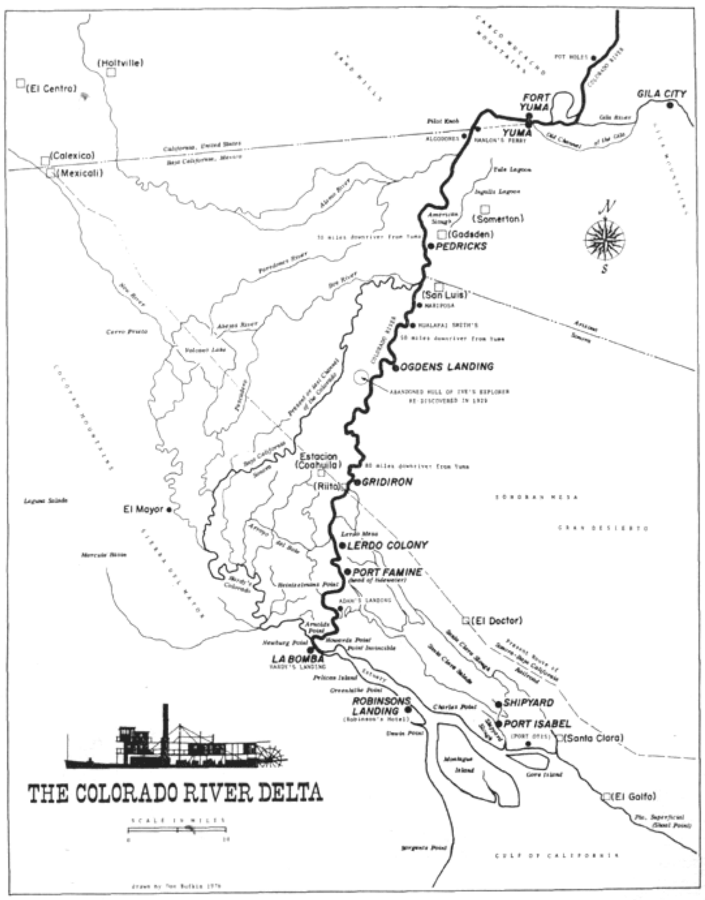

Figure 1-3 The Colorado River Delta (from the San Diego Historical Society website http://www.sandiegohistory.org/journal/81winter/mudimages.htm).

In 1944 Mexico and the USA signed a Water Treaty which guaranteed 1,850 million cubic meters of water per year (about 10% of the Colorado River's unimpaired flow) to Mexico through the Colorado River. Other issues were to be addressed through the newly created International Boundary and Water Commission (IBWC). Unfortunately, this water treaty did not address population growth or water quality. In the early 1960's as a result of drainage water from Arizona diversions, salinity exceeded the historical 1000 ppm level (Garcia-Acevedo 2000). After long rounds of negotiation, in 1973 Minute 242 was signed to amend the Water Treaty. The US 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 US Imperial Dam. Minute 306 to amend the 1944 water treaty required that both countries coordinate efforts to restore the CRD including identifying additional sources of water.

Salinity and flow regimes determine vegetation coverage in the CRD (Zengel *et al.*). However, Clinton *et al.* (2001)and others (Zamora-Arroyo *et al.* 2001) argue the main cause of CRD environmental problems is low flow regimes. 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). Other causes of the low-flow regime to the CRD are increasing population in the fast growing cities in northern Baja California. Salinity has increased from disrupted water and drainage flows from upstream diversions (Cohen and Henges-Jeck 2001). Vandersande *et al.* (2001) argue salt tolerant plant species out-compete native plant species under low flow regimes. Once invasive species are established, native vegetation often does not recover. Stromberg (2001) discuss the causal relationship between flow regimes and ecosystem functions in the CRD. The riparian corridor of the CRD requires annual flows of about 40 MCM, with pulse flows of 320 MCM every four 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. However, the costs and regional management of dedicated flows are largely unexplored.

1.4.4 Agricultural and Urban Water Uses

Water assigned to all five cities is 197,358 thousand cubic meters per year. Most (82%) goes to the large cities of Mexicali via de *Independencia* Canal and east to Tijuana and Tecate through the *Reforma* canal and then through the Colorado River-Tijuana aqueduct. Mesa Arenosa groundwater has been assigned for urban use mostly west of the Colorado River (with the exception of SLRC), but for operational efficiency the cities at the west are supplied by the surface irrigation whereas SLRC and irrigation east of the Colorado River use the Mesa Arenosa water.

Water in urban centers is mostly for residential consumption. For Mexicali, yearly average consumption (2000-2005) is 75% residential, 10% commercial, 8% industrial, and 7% government (CESPM 2006). For San Luis Rio Colorado, residential consumption is roughly 89% of total consumption (OOMAPAS 2006).

The Colorado River Delta is unique for the empirical application of the methodology proposed by this research. First, hydrology is fairly simple in the sense there is always a lower bound for water available as a result of the 1944 Water Treaty and extensive water storage upstream in the US. Rainfall in the CRD region is so scarce that it is an insignificant contribution and all agriculture is essentially irrigated. Second, there is no surface storage capacity other than the existing conveyance infrastructure. Water in excess of the Water Treaty quota is used either for artificial aquifer recharge or to provide water to early agricultural activity in the Mexicali Valley. Third, as reservoirs are essentially absent and topography of the CRD does not allow this kind of infrastructure, there is no opportunity cost of water devoted (or stored) for hydropower generation. This is an important departure from reservoir systems upstream, whose operation depends to a great extent on power demand. Fourth, agriculture in the Mexicali Valley and fast growing border cities rely almost entirely on Colorado River water. This situation is unlikely to change as the costs of alternative sources such as seawater desalination remain high. Fifth, valuation of instream flows in the delta through non-market valuation techniques such as contingent valuation and travel cost methods may pose a challenge to the researcher; as recreation and aesthetics uses through ecotourism in the region are in a very early stage.

The methodology proposed for this research does not require an *environmental water demand curve.* As explained, this estimation would come from traditional non-market valuation techniques such as contingent valuation or travel cost methods, which in this author's knowledge do not exist for the CRD. Instead, off-stream demand curves are valued and used to indirectly obtain opportunity cost of environmental water uses.

Finally, the CRD's threatened ecosystem richness has been a salient issue for conservationists and even governments in the last ten years. Emerging institutional development for water transfers as well as scant research on off-stream water value in the region invite further work on this study site.

1.4.5 Policy Analysis of Dedicated flows for the Colorado River Delta

This dissertation explores several water management alternatives to provide the Colorado River Delta with current recommended minimum flows, to maintain ecosystems functions (from Pitt *et al.* 2000). Agricultural and urban water demands projected to year 2020 are used to estimate water allocation under economically optimal scenarios considering scarcity costs, physical and institutional constraints. For Policy analysis, different levels of minimum flows are analyzed. Sources of water include idealized water markets within Irrigation District 014, infrastructure changes and wastewater reuse. Water markets are not limited to northern Baja California. The possibility of buying out water from agriculture in California or Arizona is considered. For the case of California, opportunity costs for agricultural use are obtained from previous CALVIN studies (Jenkins *et al.* 2004, Pulido-Velazquez *et al.* 2004).

The following two chapters present the economic valuation of water for agricultural and urban uses. As self-contained blocks, these two chapters have their own literature review on agricultural and urban water demand respectively. A fourth chapter describes in detail systems analysis as used in this study to value water for environmental purposes. Policy simulations and results of policy simulations will occupy the second half of this fourth chapter. A fifth chapter offers conclusions on the findings of this study.

Chapter 2 A Partial Equilibrium Agricultural Production Model for the Mexicali Valley

2.1 Introduction

Agriculture is the largest water user in many parts of the World. This chapter discusses economic water valuation for irrigation purposes. Much literature has been devoted to study water as a production input in agriculture. This study offers valuation using an empirically-calibrated deductive technique known as positive mathematical programming (PMP), after Howitt (1995). For this model, a profit maximizing farm or group of farms with similar production technology employ irrigation water. This particular application of PMP extends the Statewide Agricultural Production model or SWAP (Howitt *et al.* 2001), an input for the larger California Value Integrated Network model or CALVIN (Jenkins *et al.* 2001, Jenkins *et al.* 2004). SWAP provides shadow values of water for agriculture to be used later to estimate costs of water scarcity.

Irrigation District 014 in the midst of the Mexicali Valley is offered as a case study. Data on monthly water deliveries, per crop and irrigation sub-district are used. This application of PMP offers improvements over previous PMP studies in developing countries including Mexico (*e.g.* Tsur *et al.* 2004), as a less restrictive production function and a higher level of disaggregation are employed. Results show that shadow values for water are more sensitive to scarcity for farms located near the river with less saline soil, high value crops and access to groundwater. The estimated average price-elasticity of irrigation water at observed levels of water usage falls within the range of estimates in literature (Scheierling *et al.* 2006). Zones in the district with less favorable conditions for agriculture are prone to become sellers of water in the Mexicali Valley to support high-value agriculture, urbanization or even restoration in the Colorado River Delta.

2.2 Literature Survey

Economics of irrigation and specially water price-elasticity estimation have been studied in literature since the 1960s (*e.g.* Moore and Hedges 1963). In a meta-analysis of irrigation water demand literature, Scheierling *et al.* (2006) found that price-elasticity of irrigation water averaged -0.48 with a median of -0.16, both values falling in the inelastic range. Estimates were also found sensible to the methodology employed. Scheierling *et al.* (2006) suggest that elasticity estimates using mathematical programming or econometric estimations are usually higher than those obtained from field experiments, due to the lack of production adjustment possibilities in this later group of models.

On production decisions and water valuation, Gibbons (1986) highlights that farmers will usually maximize profits instead of yields. Thus it is possible to grow a crop with less water than that of the ideal amount without sacrificing maximum profits. However, water at low cost for a risk adverse farmer may cause overuse. Crop mix on the other hand, is determined by net revenues and input costs according to Gibbons. For the case of non-crop specific, regional estimation of irrigation water value, the author points that literature is conclusive that valuation of irrigation typically is higher when water costs or crop values are higher. This last conclusion is challenged by Young (2005), who argues

that the equi-marginal principle applies and for a single farmer or within a region, marginal product of water for a crop mix should be the same for all crops.
Most estimation of irrigation water demand falls within inductive or deductive approaches (Young 2005). In the first category, water is a variable input, whereas in the second, water is hypothesized as a limiting factor. For the hypothesis of variable water input, a production specification is assumed and water demand is obtained as the derivative of this functional form on water. Econometric analysis typically takes this category of estimation methods. Deductive water valuation is associated with the residual net economic rent. A set of inputs other than water are multiplied by their own prices and subtracted from revenues. The difference divided by the amount of water used is presumed to be the shadow value of water. Mathematical programming falls within this category and is perhaps the most widely used method to estimate water demand. Although distinction between inductive and deductive methods has been made in the literature, new approaches using generalized maximum entropy claim to establish a continuum between those two broad valuation categories (Heckelei and Wolff 2003, Heckelei 2005, Howitt 2005).

Another category of valuation relates yields of a crop to applied water. Data usually come from controlled experiments. One underlying assumption is that other production factors do not co-vary with changes in applied water. Estimates of water value are criticized for being less related to production costs and more to crop price and water productivity (Gibbons 1986).

Inductive empirical water valuation can be performed several ways, but most often using water market transactions, econometric estimates or hedonic property valuation. Market transaction observations are a good source of information, and water lease rates are usually close to those charged by the irrigation authority. However, during a drought, empirical evidence shows increased water lease rates (Griffin and Characklis 2002). Nevertheless, Young (2005) argues that lease rates of water may provide limited information for long-term planning.

The hedonic property valuation method essentially consists of estimating the influence of water rights for irrigation on the observed price of land. Characteristics of the property along with property market transactions data are used to obtain coefficients for price *determinants* econometrically. One challenge of this approach is to locate the study site, in the sense irrigated and non-irrigated and irrigated farms should have similar characteristics to avoid omitted variable bias. It is also desirable to have enough variation in water rights among the properties, to increase reliability of the estimated coefficients.

Finally, econometric valuation has been widely used to estimate the economic value of water. Young (2005)provides details of studies that have used a Cobb-Douglas production function or even cost functions to estimate water value for both disaggregated and aggregated data. Moore *et al.* (1994) offered a multi-crop production model using micro-farm data. They found price response occurs at the extensive margin with land allocation. No apparent critique of the methods is offered by Young, although inflexibility of some functional forms and large dataset requirements are the usual concerns for this kind of techniques.

Deductive techniques based on farmer's hypothesized behavior have been criticized for providing overestimates of water value, due in many cases to omission of variables or too optimistic estimates on crop prices (Young 2005). Compared to inductive techniques based on *observed* behavior, deductive techniques have been reported to give higher estimates of water value (Young 2005, Scheierling *et al.* 2006). Residual value methods are very sensible to omitted variables. The problem exacerbates when the intention is to estimate long-term water value using a short-term model with some omitted variables.

From the deductive techniques, positive mathematical programming (PMP) was first proposed by Howitt (1995), the approach used for this study. The term positive stands for the use of observed data as part of the production specification, increasing accuracy within the profit optimization program. Applications are numerous mostly for irrigated agriculture (Howitt *et al.* 2001, Howitt 2006, Howitt and Msangi 2006). A critique of the method has been offered by Heckelei and Wolff (2003), in which it is argued that PMP is not well suited for datasets with multiple observations. According these authors, marginal cost conditions prevent consistent estimation of parameters in the quadratic cost function. Howitt (2005) proves estimates are consistent but recognizes that PMP alone is best for minimal datasets.

PMP has several advantages over other traditional estimation methods of shadow values of water. First, the PMP cost function calibrates exactly to observed values of production output, and factors usage. Second, PMP adds flexibility to the profit function by relaxing the restrictive linear cost assumption. A third advantage is that PMP does not require large datasets to as many inductive methods do, to provide enough price variability.

With respect to previous programming applications in both developed and developing countries including Mexico (*e.g.* Florencio-Cruz *et al.* 2002, Tsur *et al.* 2004), the model of this study offers a less-restrictive production functional form and a richer dataset. Additionally, this application provides greater spatial disaggregation and heterogeneity, as results from this modeling study are intended for a larger scale regional application.

2.3 Model

A multi-region and multi-crop program is proposed for this study following Howitt (1995, 2006). A profit maximizing representative farmer is assumed for each group of farmers. Heterogeneity in production is addressed in two dimensions namely crops and farm groups. The unit of analysis is then a group of producers with similar characteristics per crop.

Estimation takes place within the context of positive mathematical programming (Howitt 1995), as a self-calibrating three-step procedure. First step, a linear program for profit maximization is solved. In addition to the traditional resource and non-negativity constraints a set of calibration constraints is added to restrict land use to observed values. The second step is parameterization of a quadratic cost function and the production function itself. LaGrange multipliers from the binding calibration constraints in the first step are used to estimate slope and intersect of the average cost function. A third and last step incorporates the parameterized cost functions into a non-linear profit maximization program, with constraints on resources only. Marginal values of water are obtained by restricting the resource for each unit of analysis.

2.3.1 Production Function

A Constant Elasticity of Substitution (CES) production function is proposed, following parameterization suggested in Howitt (2006). The same elasticity of substitution is assumed for all crops and all regions. The formulation adapted from Beattie and Taylor (1985) for the generalized CES production function is:

$$Y_{gi} = \tau_{gi}\left[\sum_j \beta_{gij} X_{gij}^{-\rho}\right]^{-\upsilon/\rho} \qquad (2.1)$$

Sub-index *g* is for the group or region, *i* refers to crops, and *j* to production factors or inputs. The model of this study has four inputs namely, land, labor, water and supplies such as fertilizer, pesticides and machinery time. Also in equation 2.1 above, Y_{gi} represents the output for crop *i* in region or group *g*. The scale parameter of the CES production function is referred as τ_{gi}, whereas the share parameters for the resources for each crop, are represented by β_{gij}. The X_{gij} denotes usage of factor *j* in production of crop *i* of region *g*.

The functional form is homogeneous of degree υ, and the elasticity of substitution σ is given by $\sigma=1/(1+\rho)$. The function coefficient (returns to scale) is also given by parameter υ. Some implicit simplifying assumptions for this model include an equal elasticity of input substitution for all crops and regions, and linear homogeneity in the same fashion. Strict concavity properties will be crop and region dependent. Beattie and Taylor (1985), prove that strict concavity exists when $\tau>0,\ 0<\beta<1,\ 0<\upsilon\leq 1$ and $\rho>-1$. In addition if $\upsilon+\rho>0$, complementarities in production factors are expected.

2.3.2 Positive Mathematical Programming

The first step in PMP is devoted to obtaining marginal values from the calibration constraints to parameterize a quadratic cost function in the second step. The linear program with calibration constraints is as follows:

$$\text{Max} \prod_{x_{gi,land}\geq 0} = \sum_g \sum_j v_{gj}\, yld_{gj}\, x_{gi,land} - \sum_g \sum_j \sum_i \omega_{gji} x_{gji} a_{gji} \qquad (2.2)$$

$$Ax = b \qquad (2.3)$$

$$Ix \leq \tilde{x} + \varepsilon \qquad (2.4)$$

$$Ix \geq \tilde{x} - \varepsilon \qquad (2.5)$$

Equation 2.2 is the objective function of the linear program. The decision variable $x_{gi,land}$ refers to the total acres planted for region or group *g* and crop *i*. The marginal revenue of crop *i* in region g, is given by v_{gi}. Average yields and average costs are given by yld_{gj} and ω_{gji} respectively. The Leontief coefficients a_{gji} in the A matrix are given by the ratio of total factor usage to land. In other words, all production inputs are normalized with respect to land, therefore $a_{gi,land}$ is expected to be one unit for all crops and regions.

Equations (2.3-2.5) are in matrix form. In the resource constraint set (equation 2.3), matrix **A** is three-dimensional (G I K) with regional Leontief coefficients a_{gkj} as elements. K is a subset of the resources set, that includes only those resources in limited amounts. In the same equation, **x** is a column vector of dimensions K by 1 of the decision variable $x_{gi,land}$. Vector **b** is the regional limit on the resource with dimensions J by 1. The last two sets (2.4 and 2.5) are for the upper and lower bounds of the calibration constraints, where **I** is a J by J identity matrix, the *x-tilde* is the observed value of resources usage, whereas ε is small perturbation to make limited resources *k* bind.

The second step in PMP estimation has the purpose of calculating parameters needed by the quadratic cost function and the CES production function. The cost function is given by equation (2.6) below:

$$TC_{gij}(x_{gij}) = \alpha_{gi} x_{gij} - 1/2 \gamma_{gi} x_{gij}^2 \qquad (2.6)$$

Where the parameters α_{gij} and γ_{gij} correspond respectively to intersect and the slope of a linear marginal cost function for factor *j*, crop *i* in region *g*. Since average costs ω_{gij} in the objective function (2.2) are variable and assuming the marginal revenue equals marginal cost.   Howitt (2006) proves that:

$$\gamma_{gi} = \frac{v_{gi} yld_{gi}}{\eta_{gi} \tilde{x}_{gij}} \qquad (2.7)$$

Where η_{gi} is the price-elasticity of supply for crop *i* in region *g*. Thus policy response on this formulation will depend on empirical information on supply response which sometimes is not readily available. One shortcoming of this approach is that positive net returns are not guaranteed. Average cost on the other hand is given by:

$$AC_{gij}(X) = \alpha_{gij} - 1/2 \gamma_{gij} \tilde{x}_{gij} \qquad (2.8)$$

where $AC_{gi} = \omega_{gij}$ and the rest of the values are known. This yields,

$$\alpha_{gij} = \omega_{gij} + \lambda_{2,gij} + \gamma_{gij} \tilde{x}_{gij} \qquad (2.9)$$

where $\lambda_{2,gij}$ is the dual value of the binding calibration constraints set in equation 2.4 above. One of the issues with this approach is the underlying assumption that the marginal crops, those constrained by resources, have constant marginal costs whereas profitable unconstrained crops may have increasing cost functions. This is addressed using the following adjustment term (Howitt 2006):

$$\tilde{\lambda}_{2,g,r,j} = \lambda_{2,g,r,j} + Adj_{grj} \quad \text{where } \mathrm{Adj}_{\mathrm{grj}} = \frac{v_{gr} y_{gr}}{2\eta_{gr}} \qquad (2.10)$$

And the sub-index *r* is for all non-marginal crops. Thus equation 2.9 will actually use the adjusted $\lambda_{2,gij}$ for all non-marginal crops.

The last step in PMP is to solve a non-linear constrained profit maximization program. The objective function becomes:

$$Max_{x\geq 0} \prod = \sum_g \sum_i v_{gi} Y_{gi} - \sum_{\mathrm{g}} \sum_i \sum_j (\alpha_{ig} x_{gi,land} - \gamma_{ig} x_{gi,land}^2) \qquad (2.11)$$

subject to:

$$Ax \leq b \qquad (2.12)$$

$$xm_{gm} \leq \sum_i met_{gim} x_{gi,water} \quad \forall g,m \qquad (2.13)$$

$$\sum_m xm_{g,m} \leq availwater \cdot b_{water,g} \quad \forall\, g \qquad (2.14)$$

In equation 2.11, Y_{gi} is defined by the production function of equation 2.1 above, the derivation of parameters τ_{gi} and β_{gij} is detailed in Appendix 2 . The second term in the equation has now the PMP calibrated cost function. Constraint 2.12 is as in 2.3 above, with the exception that all resources are included, not just those limited.

A new constraint set on monthly water usage has been included. Variable xm_{gm} in equation 2.13 is monthly water usage in region *g* in month *m*. Three underlying assumptions are worth discussing. First, water is interchangeable among crops within a region. Second, a farm group (or region) maximizes profits on a yearly basis, equalizing marginal revenue to marginal costs every month. The last assumption is that a region or farm group picks the crop mix that maximizes profits within the region. In other words, the shadow value of water will be the same for all months and for all crops *i* in a region or farm group *g*. This last is expected to hold (Young 2005).

The last constraint set (2.14) is for regional water in which, $b_{water,g}$ corresponds to that in the right hand side of equation 2.12 for water. The parameter *availwater* is used later to obtain a shadow value of water by constraining water regionally, such that $0 < availwater \leq 1$. Constraint set 2.14 assumes that yearly water is available in a limited amount for every region or group. Less realistically, it is also implicit that water is not traded among groups or regions, although the demand for water trading among groups can be assessed by comparing duals across regions for the water availability constraint.

A derived water demand curve is obtained by reducing the parameter *availwater* in equation 2.14 above. The program of equations 2.11 to 2.14 is solved first for roughly a hundred percent of water available (*availwater=0.999)*. The program then can be solved for conditions with incrementally less water availability to obtain a derived water demand curve.

Model CALVIN requires penalty functions or seen other way, scarcity costs of water. Shadow values in obtained in the model are used to develop a piecewise derived water demand curve. Scarcity costs are obtained by integrating the derived water demand curve using the trapezoidal rule. Appendix 1 details the procedure.

2.4 Agriculture and Irrigation Water in the Mexicali Valley

2.4.1 Agriculture and Water

The Irrigation District 014 (ID 014) *Río Colorado*, is located in the northern US-Mexico border of the Mexican states of Baja California and Sonora (Figure 2-1). This region is known as the Mexicali Valley. It has a gross area of 350,000 ha of which 250,000 ha are irrigable. The ID 014 is divided into 22 sub-districts or modules (Figure 2-1). About 208,000 hectares roughly 84% benefit from water rights for irrigation. Of these, 26,647 ha are located in the municipality of San Luis Rio Colorado, Sonora and the rest in Mexicali, Baja California. Some authors argue there is no subsistence agriculture in the MV, only commercial agriculture. Being among the most productive regions in Mexico, the agriculture in the Mexicali Valley yielded nearly 2.8 billion pesos in production value in year 2004 (SAGARPA 2006).

Agriculture ministry statistics indicate that the main three crops in the Mexicali Valley are alfalfa, cotton and wheat. In 2004 these three crops represented 77% of the total planted area and 54% of the total agricultural value. High value crops such as asparagus and green onion add 25% more to the total agricultural value. Table 2-1 below shows the main crops in the Mexicali Valley, those that represent more than 1% in cultivated land. Cultivated land from the crops in Table 2-1 is about 95% of the total in the Mexicali municipality for fiscal year 2004. More than 85% of total agricultural value in the valley is due to the aforementioned crops.

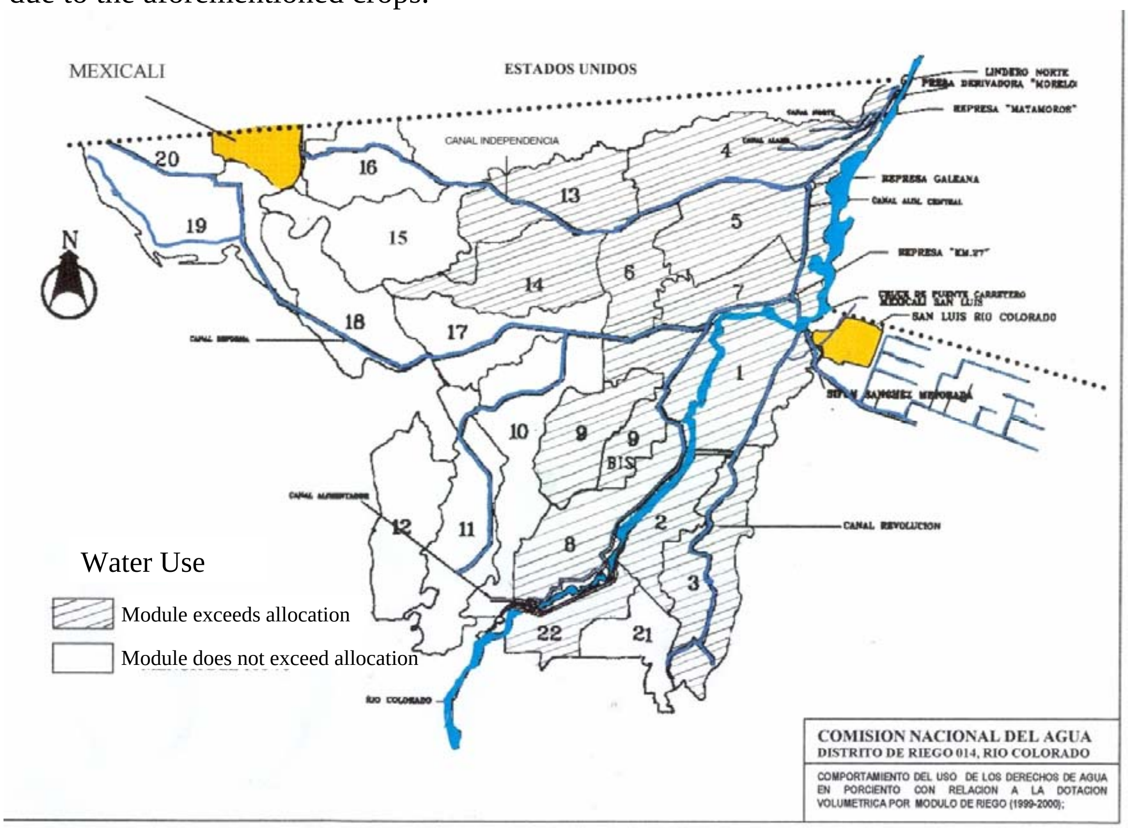

Figure 2-1 Location of the Mexicali Valley and the Irrigation District 014 modules. Shaded modules are those that usually exceed their water allocation (Source: CNA D.R. 014).

Table 2-1 Main crops and water use in the Mexicali Valley year 2004. (Sources: CNA 2006, SAGARPA 2006)

Crop Name	Cultivated Land (ha)	Crop Land (ha)	Production Ton	Yield (Ton/ha)	M.R.P.* ($/Ton)	Production Value (000's $)	Water Usage (TCM/ha)
Alfalfa	25,517	25,517	1,931,036	75.68	240	463,449	14.77
Asparagus	2,077	2,057	9,583	4.66	39,600	379,494	18.03
Barley	1,685	1,589	4,638	2.92	1,600	7,421	7.17
Canola	2,993	2,869	5,116	1.78	2,470	12,636	4.25
Cotton	17,697	17,686	71,076	4.02	3,748	266,417	11.38
Green Onion	4,111	4,106	48,826	11.89	6,862	335,064	5.82
Rye Grass	5,446	5,369	224,677	41.85	199	44,598	6.96
Sorghum Forrage	5,344	5,155	315,260	61.16	167	52,648	9.32
Sorghum Grain	7,118	6,946	31,257	4.50	1,350	42,197	7.84
Wheat	85,773	85,320	425,667	4.99	1,807	769,050	8.34
Total	157,761	156,614	3,067,137			2,372,975	

*M.R.P stands for mean rural price. About 27,000 ha in San Luis Rio Colorado, Sonora were not part of this statistic.

Water usage per hectare in the Irrigation District 014 is also detailed in Table 2-1. Alfalfa, cotton and wheat take most of the water. In the entire Mexicali Valley these crops together take almost 1,500 MCM/yr, roughly 72% of all water use in the ID 014.

2.4.2 Water management and distribution in the ID 014

To better understand the interaction of institutions and hydraulic infrastructure in ID 014, a brief description of water management and its distribution is offered. The starting point for surface water is the US-Mexico border, where the Mexican section of the International Boundary and Water Commission (CILA), oversees water deliveries from US at two points namely, the Morelos Dam and the *Lindero Sur.* At the first point the US delivers a minimum of 1,677,234 thousand cubic meters per year. The Lindero Sur receives 173,000 thousand cubic meters yearly. Surplus of water from the US are distributed within the district either for pre-deliver water to some early crops in the *water year*, artificial aquifer recharge, or ecological use in the Colorado River Delta (González-Cobarrubias *et al.* 2001).

Once CILA receives and delivers water, Irrigation District 014 has four levels of control, operation and maintenance of water conveyance infrastructure. At the first level of control is CNA through the *Jefatura de Distrito de Riego 014.* The Jefatura oversees 27 km of the Main Canal *(Canal Principal*) that goes from the Morelos Dam to the *Represa Km. 27*. Artificial aquifer recharges can be carried by CNA through *Del Norte* and *The Alamo* Canals, by diverting water at the *Matamoros* diversion dam, the first *control point* in the system. The second control point is the *Galeana* diversion dam that takes water to the canal Independencia to feed potable water facilities in city of Mexicali. The main control point in the system is the Represa KM 27 diversion dam where water is distributed to canals Reforma and Revolución. The Lindero Sur deliveries from the US travel through the canal *Sanchez-Mejorada* to mix at a point known as *La Licuadora* with water from the KM 27 diversion. A third supply of water mixed in La Licuadora is that from the Mesa Arenosa de SLRC aquifer, via the *canal colector.*

At the second level of control, the CNA’s Jefatura also delivers water to the Limited Responsibility Users’ Association or *Sociedad de Responsabilidad Limitada* (SRL) of ID014. This user organization operates and maintains the main canals and wells of the ID

014 and distributes water through three delivery units. The main network of Irrigation District 014, includes the canals: Reforma, del Norte, Independencia, Delta 2, Alimentador del Sur, Revolución and Barrote (Figure 2-2). Together they total nearly 293 kilometers (González-Cobarrubias *et al.* 2001). More than 88 control gates, and 460 secondary canals and diversions are controlled by lower level module organizations. The first unit or *Primera Unidad* is for Canal Independencia supplying modules 4,5,6,7,14,15 and 16. The second unit uses Canal Reforma to deliver to modules 8,9a, 9b, 10, 11, 12, 17, 18,19, and 20. The Tercera Unidad uses Canal Revolución to deliver water to modules 1,2,3, 21, and 22.

At the third level of control, there are 22 irrigation sub-districts or *modules* which are legally established as civil water user associations (Figure 2-2). These user associations have concessions for operation and maintenance of the secondary network of canals. Module 13 was dissolved by the Irrigation District 014 CNA office in 2004-2005[1]. Area from Module 13 was transferred to modules 4, 15 and 16. Final users within irrigation modules conform the fourth level of control in the irrigation district. There are a total of 16,411 users within the 22 modules covering 208,215 hectares in the Mexicali Valley. This averages 12.7 hectares per user with water use rights. Conveyance efficiency is defined as the ratio of water delivered to the module divided by water provided at the primary canal network. Weighted 1998-2005 conveyance efficiencies per module range between 75 and 99% for ID 014. Conveyance efficiency is the highest for modules which primary water source is groundwater extraction. The overall average conveyance efficiency in the Mexicali Valley is 90%.

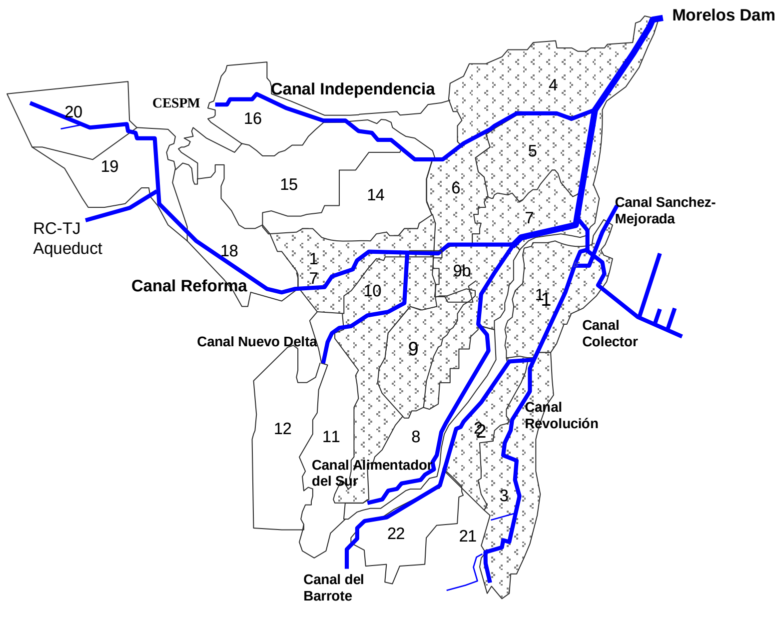

Figure 2-2 Main canals and the modules in the Irrigation District 014 (Source: CNA D.R. 014).

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[1] This change is not reflected in most of the figures in this study.

Irrigation District 014 CNA office (*i.e.* the *Jefatura de Distrito*) has authority to schedule water deliveries in consensus with the SRL and the modules. The irrigation plan in ID 014 is known as the *Cédula de Irrigación.* CILA, the Mexican section of the IBWC coordinates with its American counterpart and the Bureau of Reclamation to provide deliveries required in the Cédula.

Soil quality in ID 014 plays a key role on both yields and land rental prices. Soil has been classified into six types in descending quality order from first to sixth quality soil. Figure 2-3 below shows that land near the river (Northeast), north and central zones of ID014 have the largest proportion of first and second quality soils. This is reflected in Table 2-2 below. Worst soil quality seems to be located in the North East MV, close to the city of Mexicali. Modules 1, 3, 4, 5,6, 9a, 9b and 11 are privileged with about 90 % soil first and second class soil quality. In the middle range are modules 2, 7,8, 10, 12, 14 and 16. The modules are 3, 15 and 17-22 have poorer soils.

Table 2-2 Classification of soil quality per module in the Irrigation District 014.

Module	Land Area (ha)	Land w/ water use rights (ha)	Classification of Soil Quality by Module												
			1^{era}	%	2^{da}	%	3^{era}	%	4^{ta}	%	5^{ta}	%	6^{ta}	%	% total
1	***12,582***	***11,160***	8,617	68.49	2,900	23.05	705	5.60	230	1.83	70.00	0.56	60	0.48	100
2	***6,986***	***6,719***	1,396	19.99	3,680	52.67	845	12.09	630	9.02	130.00	1.86	305	4.37	100
3	***13,550***	***9,818***	6,600	48.71	2,835	20.92	1,645	12.14	895	6.60	240.00	1.77	1,335	9.85	100
4	***16,423***	***13,600***	7,913	48.18	6,625	40.34	1,065	6.48	290	1.77	70.00	0.43	460	2.80	100
5	***9,771***	***9,916***	6,221	63.67	2,790	28.55	445	4.55	70	0.72	35.00	0.36	210	2.15	100
6	***7,113***	***6,357***	5,103	71.74	1,450	20.38	285	4.01	225	3.16	30.00	0.42	20	0.28	100
7	***13,699***	***13,038***	8,294	60.54	3,690	26.94	1,385	10.11	220	1.61	0.00	0.00	110	0.80	100
8	***11,522***	***10,509***	8,452	73.35	1,185	10.28	1,220	10.59	350	3.04	125.00	1.08	190	1.65	100
9-a	***8,796***	***9,492***	7,096	80.67	975	11.09	535	6.08	60	0.68	130.00	1.48	0	0.00	100
9-b	***10,961***	***10,168***	9,146	83.44	1,665	15.19	60	0.55	0	0.00	0.00	0.00	90	0.82	100
10	***14,918***	***13,156***	5,418	36.32	5,130	34.39	1,620	10.86	985	6.60	690.00	4.63	1,075	7.21	100
11	***9,938***	***9,334***	5,413	54.47	3,825	38.49	410	4.13	85	0.86	125.00	1.26	80	0.81	100
12	***12,205***	***9,554***	6,685	54.77	2,575	21.10	2,080	17.04	500	4.10	70.00	0.57	295	2.42	100
14	***10,750***	***8,817***	5,700	53.02	3,175	29.53	1,490	13.86	235	2.19	70.00	0.65	80	0.74	100
15	***15,941***	***12,804***	4,421	27.74	5,465	34.28	5,055	31.71	590	3.70	160.00	1.00	250	1.57	100
16	***17,157***	***11,925***	8,897	51.86	5,260	30.66	1,830	10.67	400	2.33	250.00	1.46	520	3.03	100
17	***11,842***	***9,193***	1,922	16.23	5,440	45.94	1,130	9.54	435	3.67	130.00	1.10	2,785	23.52	100
18	***11,378***	***7,852***	1,308	11.49	4,420	38.85	3,865	33.97	1,030	9.05	480.00	4.22	275	2.42	100
19	***11,330***	***8,023***	480	4.23	2,585	22.82	6,690	59.05	740	6.53	95.00	0.84	740	6.53	100
20	***8,953***	***5,026***	1,898	21.20	3,415	38.14	2,665	29.77	540	6.03	435.00	4.86	0	0.00	100
21	***7,017***	***6,836***	2,602	37.08	1,700	24.23	1,485	21.16	100	1.43	615.00	8.76	515	7.34	100
22	***7,168***	***4,916***	1,093	15.25	2,725	38.02	2,820	39.34	0	0.00	150.00	2.09	380	5.30	100
Total I.D.	***250,000***	***208,215***	***114,675***	***45.87***	***73,510***	***29.40***	***39,330***	***15.73***	***8,610***	***3.44***	***4,100.00***	***1.64***	***9,775***	***3.91***	***100***

Strata is within the range of 30-60cm. Source: CNA D.R. 014.

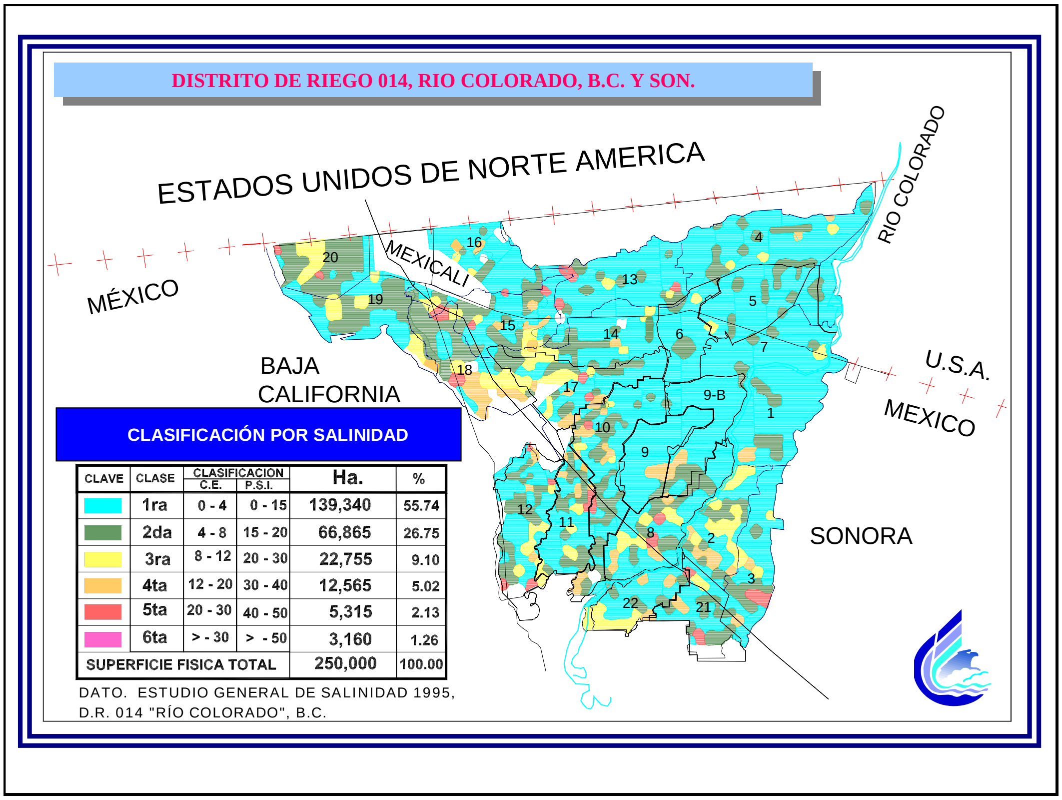

Figure 2-3 Soil quality in the Irrigation District 014 (Source: CNA D.R. 014).

Interestingly, water selling modules and water demanding modules mimic this pattern (Figure 2-1). Modules in the east half of the valley tend to demand more water than their assignment. There was no readily available information on yields per crop at a module level. Nevertheless land rental price was used as a proxy for heterogeneity using information from Table 2-3 as follows:

$$YF_g = \frac{\left(\sum_q \overline{\omega}_{g,q,land} x_{g,q,land}\right) {}^{1}\!\Big/\!{\sum_q x_{g,q,land}}}{\frac{1}{\sum_q x_{g,q,land}} \sum_g \left[\left(\sum_q \overline{\omega}_{g,q,land} x_{g,q,land}\right) {}^{1}\!\Big/\!{\sum_q x_{g,q,land}}\right]} \quad (2.15)$$

Where YF_g is the yield factor, and equals the ratio of weighted average land rental price in a module g and the weighted average rental price in the district. The weighted land rental price $\omega_{g,q,land}$, corresponds to the fourth column in Table 2-3, whereas the variable $x_{g,q,land}$ refers to the land area of irrigation module g (second column in Table 2-2). The yield factor multiplies average yields (*e.g.* Table 2-4 below) in the irrigation district to give an *equivalent yield.*

Table 2-3 Land rental prices (in MX Pesos) by soil quality class for water year 2005.

Soil Class	Min	Max	Average
First	3,000	4,000	3,500
Second	2,000	2,500	2,250
Third	1,200	2,500	1,850
Fourth	500	1,200	850
Fifth	500	500	500
Sixth	500	500	500

Souce: Verdin, Personnal Communication.

2.5 Data

The model requires several datasets including, planted acres, factor usage, market price of products and factors in the study site. This section describes data, its use and sources. These sources include digital databases and reports from SAGARPA, CNA and Baja California State Agencies. A crop mix was selected for this study based on significance of cultivated land. Water Year 2004-2005 was the base year for both factor usage and costs. The crop mix for this study is described in Table 2-4. Considering a total of 182,030 hectares for irrigation that year for the crops on the CNA's 2005 Water Deliveries Report (CNA 2006) and a volume of 1,981,905 thousand cubic meters; this crop mix covers roughly 85% of the cultivated land and slightly more than 83% of the water delivered in the Mexicali Valley for irrigation purposes.

Four production factors were considered in this study, namely land, water, labor and supplies. With the exception of water and land, labor and supplies were assumed to be the same for all the modules in the irrigation district. Thus implicitly, heterogeneity in production at the module level is addressed through different land and water usage, crop mix and the *equivalent yield* (equation 2.15 above). For this last parameter, estimates ranged from 0.70 to 1.25.

Table 2-4 Crop mix for model SWAP in the Mexicali Valley (from CNA 2006)

Crop Name	Cultivated Land (ha)	Average Yields (Ton/ha)	Water Delivered (000's m3)
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*

2.5.1 Planted Acres and Water Deliveries

Information on planted acres was available for six *water-years*[2] from 2000 to 2005. There are at least two sources for this data. The first one is the Agriculture Ministry (SAGARPA) online databases in SIAP (htpp://siap.sagarpa.gob.mx). These databases provide information on planted land, cropped land, yields, mean rural price, and production value. Time series for these variables go from 1980 to 2004 for several crops. For the state of Baja California, two municipalities lead agricultural production namely Ensenada and Mexicali. Ensenada is not an irrigation district but an *irrigation unit* instead, mostly using groundwater. Agriculture in Ensenada is outside the scope of this study. The municipality of Mexicali covers most of the ID 014, except that part in the state of Sonora. Fortunately, SAGARPA statistics disaggregated agricultural production also in *Distritos de Desarrollo Rural or DDR*, there is one DDR that corresponds to the Colorado River and includes both municipalities of Mexicali and San Luis Rio Colorado.

A second source of information for planted land is the Office of Statistics of Irrigation District 014 through their annual Water Use Report or *Informes de Distribución de Aguas*. Electronic databases provide information on planted acres, and monthly water deliveries per crop group and module. These deliveries are classified by water source either surface or groundwater. Monthly water deliveries were used to establish a seasonal water use pattern for the Mexicali valley for each irrigation module. No distinction on municipality is evident in these statistics since they adhere to module geographical delimitations. However, modules 1, 2 and 3 are located in the municipality of SLRC.

2.5.2 Factor Usage and Costs

Factor usage information and costs were also available from several sources including Irrigation District 014 Statistics Office and from the state office of the SAGARPA, and a study on the All American Canal Lining (Fuentes *et al.* In press). Average production costs and mean rural product prices were available for some water years from 2000-2005. Cost information for some crops was detailed but for others it was very scant. Nevertheless data for the crop mix selected for this study (Table 2-4) was reasonably solid and consistent among state and federal agencies including mean rural prices for the crop output in the base year are estimates from SIAP (SAGARPA 2006).

Mean Rural Price, and factor usage is summarized below for the crop mix for this study (Table 2-5). A *jornal* (third column of Table 2-5) is an eight-hour labor period. The labor price was assumed to be $100 per jornal for all crops and all modules. Water fee from 2001-2005 has been $70 Pesos per thousand cubic meters. Other supplies were not itemized in the cost information as such. Instead these were approximated from the SAGARPA's total variable cost not-related to water or labor. The units of these were in pesos, although they were scaled to tens with a unit cost of ten pesos[3].

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[2] In this study, a *water-year* is the one that starts in October of one year and finishes in September of the following year. For simplification purposes, *water year* 1999-2000 would be referred as water year 2000.
[3] In other words, 1 unit of supplies in Table 2-5 will have a cost of ten Pesos.

Table 2-5 Mean rural price, labor and other supplies usage per hectare (Adapted from SAGARPA 2006).

Crop Name	Mean Rural Price (MX $/Ton)	Labor (Jornales/ha)	Supplies (tens per/ha)
Alfalfa	240	13	161
Asparagus	39,600	71	1,430
Canola	1,900	6	300
Cotton	5,615	38	823
Green Onion	6,845	310	1,730
Rye Grass	199	7	406
Sorghum Grain	900	8	626
Wheat	1,805	6	612

2.5.3 Monthly Water Use

Monthly water delivery information per irrigation module and crop is from CNA's water delivery reports (CNA 2006). Average water deliveries per month and crop in all ID 014 are shown in Table 2-6. The numbers in the table are in percent of total annual delivery for the crop in the Irrigation District 014. This information is fundamental for the model since penalty functions for the CALVIN model (Chapter 4) are monthly.

Table 2-6 Monthly water usage per crop in the Irrigation District 014. Expressed as a percentage of the total annual delivery for the crop. (Source: CNA 2006).

Crop Name	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Alfalfa	3.5	3.6	6.4	12.2	14.3	13.9	13.4	8.1	8.8	6.0	5.0	4.8
Asparagus	4.9	3.5	7.1	8.2	12.3	11.2	15.0	13.4	12.9	5.8	0.7	5.1
Canola	9.3	14.3	21.5	26.7	2.1	0.0	0.0	0.0	0.0	0.4	10.5	15.3
Cotton	4.5	8.2	3.9	4.3	15.0	25.8	30.5	7.0	0.8	0.0	0.0	0.0
Green Onion	8.8	7.5	9.8	10.3	7.9	4.9	9.2	3.2	3.8	13.0	11.6	10.0
Rye Grass	9.0	6.1	12.3	20.8	6.8	0.3	0.0	0.0	0.0	20.6	14.8	9.4
Sorghum Grain	0.0	0.0	0.0	0.3	0.0	10.6	31.8	31.2	22.8	3.3	0.0	0.0
Wheat	11.9	13.7	25.1	25.2	1.0	0.0	0.0	0.0	0.0	1.0	7.5	14.6

2.5.4 Aggregation and Preparation for Modeling Runs in SWAP

As mentioned earlier, the main purpose of this study is to valuate water for agriculture in the Mexicali Valley. CALVIN requires penalty functions (see Appendix 1) obtained from the shadow values on the water constraint (equation 2.14). Previous applications of SWAP (Howitt *et al.* 2001) give shadows values per agricultural region in California's Central Valley. These regions known as CVPM's and have on average 141,000 cultivated hectares of representative crops. SWAP has successfully provided estimates of agricultural water value in these CVPM's for several studies under different hydrological and projected demand conditions (Jenkins *et al.* 2001, Jenkins *et al.* 2004, Tanaka *et al.* 2006).

For the Mexicali Valley, the crop mix includes more than 150,000 hectares of cultivated land in total (Table 2-4), from 208,000 hectares with water use rights. Average physical size of a module is about 11,364 hectares. As CALVIN is a large-scale regional model, that includes urban, agricultural and environmental demand sites, connected through a network of major hydraulic infrastructure; some aggregation is required.

Thus the 22 modules for the Mexicali Valley were aggregated into four groups based on geographical location, land quality and primary water sources. The four groups were named, East of the Colorado River, Main Valley, West of the Valley and Groundwater. Table 2-7 shows the modules for each group with their respective cultivated areas for the crop mix of this study. The area of each modulo group goes from 21,445 hectares for the East group to 55,427 in the case of the West side group.

Table 2-7 Cultivated land (in hectares) by module group for the selected crop mix of the Mexicali Valley. (Source: CNA 2006)

Group	Name	ALFAL	ASPAR	CANLA	COTTN	GRNON	RYEGR	SRGFR	WHEAT	Grand Total
EAST	Módulo 1	1,584	208	0	1,101	141	19	59	4,944	8,056
	Módulo 2	970	108	127	789	267	0	103	2,177	4,541
	Módulo 3	663	407	376	1,947	453	6	77	4,919	8,848
EAST Total		**3,217**	**723**	**503**	**3,837**	**861**	**25**	**239**	**12,040**	**21,445**
GROUND	Módulo 4	1,209	322	4	2,111	89	8	46	4,984	8,773
	Módulo 5	981	0	3	2,899	279	2	9	4,711	8,884
	Módulo 6	804	20	0	1,237	96	6	68	3,195	5,426
	Módulo 7	1,187	0	0	1,925	409	0	0	3,752	7,273
	Módulo 9a	1,726	175	75	189	1,036	42	96	2,428	5,767
	Módulo 9b	1,381	243	107	526	1,236	3	64	2,063	5,623
GROUND Total		**7,288**	**760**	**189**	**8,887**	**3,145**	**61**	**283**	**21,133**	**41,746**
MAIN	Módulo 10	3,507	100	209	585	120	501	316	5,691	11,029
	Módulo 11	982	52	531	687	0	207	196	5,174	7,829
	Módulo 12	1,347	16	320	619	0	136	178	5,122	7,738
	Módulo 14	1,402	0	16	1,949	54	75	288	5,355	9,139
	Módulo 17	1,934	0	156	377	0	349	249	4,854	7,919
	Módulo 22	1,916	0	69	214	0	120	73	2,333	4,725
	Módulo 8	1,096	86	333	278	266	122	137	4,730	7,048
MAIN Total		**12,184**	**254**	**1,634**	**4,709**	**440**	**1,510**	**1,437**	**33,259**	**55,427**
WEST	Módulo 15	1,728	20	118	1,234	0	712	352	6,064	10,228
	Módulo 16	2,172	83	0	1,960	42	297	291	3,266	8,111
	Módulo 18	390	105	6	17	0	1,547	218	2,335	4,618
	Módulo 19	581	20	11	40	0	288	58	2,141	3,139
	Módulo 20	61	0	18	0	0	200	85	2,096	2,460
	Módulo 21	752	74	270	533	0	71	242	2,500	4,442
WEST Total		**5,684**	**302**	**423**	**3,784**	**42**	**3,115**	**1,246**	**18,402**	**32,998**
Grand Total		**28,373**	**2,039**	**2,749**	**21,217**	**4,488**	**4,711**	**3,205**	**84,834**	**151,616**

The East group consists of modules on the east side of the Colorado River in the state of Sonora (modules are 1, 2, and 3). Module 1 has the best land quality, although adding modules 2 and 3 makes average land quality equal to that at the district level. The shadow value of water for this group is expected to be higher than the average for the district, since geographic location has benefits and high value crops such as asparagus and green onion are well represented.

A second group of modules has relatively high use of groundwater for irrigation. These include modules 4, 5, and 7 which happen to be in the US-Mexico border with Arizona and devote at least 22% percent of their crop area to cotton. Wheat is the most common crop in ID 014 in terms of land share. Nevertheless, the groundwater group has less than the district average of 56%. Modules 9a and 9b have a higher share of green onion and alfalfa. Module 6 devotes land mostly to the district's top three crops, alfalfa, cotton and wheat.

The Main Valley is the third group of modules. Besides the location of most of modules being roughly at the center of the district, another characteristic of the group is the higher use of surface water. Modules 8, 10, 11, 12, 14, 17 and 22 are included in this group. Most modules in this group devote production to alfalfa and wheat. Higher value crops such as asparagus green onion are less present for this group.

Finally, lower value crops, water surplus and a higher share of lower quality, characterize west side agriculture. Modules 15, 16, 18, 19, 20, are usually considered water *donors* (Figure 2-1). Interestingly, cultivated land follows about the same pattern as for the Main Valley group and even higher value crops have relatively more area than the center of the valley. However, after the three main crops, forages have the second place in importance.

2.6 Model Runs and Results

The datasets detailed in the previous section were used to run the PMP model. To obtain derived demand curves for water for each of the four irrigation groups, water availability was limited from 99% down to 60% in ten percent steps. As explained before, the water constraint (equation 2.14) is regional. Thus, water is assumed to be interchangeable within the group of modules, and the marginal product of the optimized crop mix will equal its marginal cost.

A code in GAMS™ (General Algebraic Modeling System htpp://www.gams.com) was prepared to run the PMP model with the CES production function. A template from previous applications by Howitt (Howitt *et al.* 2001, Howitt *et al.* 2003, Medellin-Azuara *et al.* 2006) was used. To read CNA databases for water deliveries a macro in Microsoft Visual Basic for Applications was programmed to accommodate the pertinent information into a Microsoft Excel™ sheet master database. From this master database, it was possible to elaborate dynamic data tables in a format suitable for GAMS™ via GDX utilities. The code included four steps; the first step was devoted to linear profit maximization (equations 2.2 to 2.5). In the second step the calibration parameters were estimated and carried to the third step (equations 2.11 through 2.14). Parameterization loops to obtain derived demand curves and output to spreadsheets followed.

Calibration of the model to observed values was verified in the first and third steps. The criteria were first, difference in input usage and second, difference in output for all regions and all crops. In addition, the model was checked for non-positive net revenues. In most cases the percent difference of input usage was in the order of $1x10^{-6}$, for both stages. The exception was rye grass in group 1 (East), with a percent difference in input allocation of -2.019 %. No apparent reason for this difference was found; this difference represents about 95 ha of land or 0.06% of total crop area of this study.

Results of the water availability parameterization runs are shown in Table 2-8. Overall, agriculture in the west of the Mexicali Valley seems to have the lowest shadow value of irrigation water when availability drops below 80%. The main valley has the highest value step by step whereas the east side keeps a shadow value just in the average of the four regions. In Figure 2-4, the shadow value of water use for the groundwater-dependant area has the widest range (see also Table 2-8).

Table 2-8 Water shadow value in the Mexicali Valley.

	Shadow Value (Pesos /000's m3)			
Water Availability (%)	*East*	*Main*	*West*	*Groundwater*
100	270	402	233	186
90	327	452	279	253
80	388	502	346	336
70	451	547	418	434
60	512	584	489	546

Figure 2-4 illustrates behavior of each region. The East group for example represents only 15% of the total water for the mix in this sample, whereas share of the Main valley is 35.4%.

Compared to water fees paid by farmers from CNA (CNA 2005) statistics, shadow value of water is the lowest at full availability for groundwater agriculture. A value of $186 pesos per thousand cubic meters is 2.67 times the fee paid for that water year of $69.44 pesos for the same amount of water. According to CNA officials at ID 014 (H.Verdín, Personal Communication, May 2006), the market price for water is about $700 pesos per hectare. Hectares have a volumetric allocation of about 100 cm or 10,000 cubic meters. Thus market price for water is roughly the water fee paid. Although extreme conditions of scarcity modeled (60%) will increase the ratio of current value to current price from 2.67 to 7.86, the second highest among the four regions. An argument for such a drastic change in water value relative to other regions is that water use intensity (as volume per hectare) is higher for water intense crops. However, region one has the highest *yield factor* (equation 2.15) of 1.16. As water becomes scarce, the high marginal product of water for this *high-yield* region drives the shadow value of the resource in a more drastic manner relative to other regions.

East side agriculture water value is surprising, as the shadow value is roughly the average of the valley at all levels of availability. One explanation is that Modulo 1 has an above district average yield factor of 1.16 compared to Modulo 2 with only 0.86. The other sub-district, modulo 3 has the district average yield factor. This ultimately may affect water valuation under scarcity conditions.

Valuation of water in main valley agriculture turns out higher than expected. This expectation occurs in part because the main valley has a higher concentration of the top three crops (alfalfa, wheat, cotton). These three crops however, report high net revenues. Alfalfa and wheat, representing 22% and 60% respectively, of the cultivated area in the crop mix are highly subsidized in the valley and in the rest of the country.

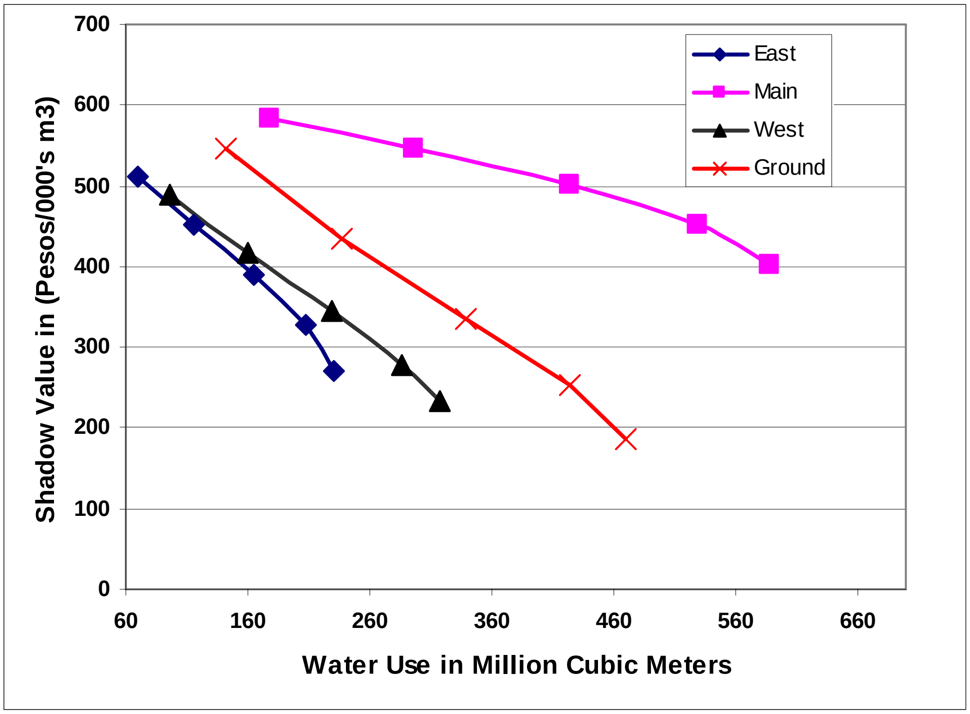

Figure 2-4 Shadow value of water in the Mexicali Valley

Finally, west side agriculture is the likely donor of water for other regions or urban uses. Low value crops and poor quality land reduce the marginal product of water. However, this does not seem to be the case for water scarcities below 20% at which the groundwater region would be a better candidate to sell water. It is unlikely that groundwater agriculture would sell water to other agricultural users. Historically, regions close to the Colorado River require supplemental water for irrigation (see Figure 2-1 above). One explanation for this erratic behavior is that price-elasticity of supply (η_{gi} in equation 2.7 above) is assumed to be the same for all crops and all regions. As better information on this parameter is obtained from econometric studies in the valley, a more precise estimated response would be obtained. Regions with a higher value crop mix would respond more drastically to even small shortages.

Average price elasticity of irrigation water in the Mexicali Valley ranged from -0.50 for conditions of relative abundance, to -0.66 at 60% water availability (Table 2-9). As expected, price-elasticity of irrigation water is higher at higher water *prices.* Estimated price-elasticities seem to fall within the range of most values found in the irrigation literature at observed levels of production (Scheierling *et al.* 2006). A surprising result is for the Main Mexicali Valley where elasticity at observed production is particularly high. The only possible explanation is the relatively large water shadow value at full availability in the Main Valley.

Table 2-9 Estimated price elasticity of irrigation water in the Mexicali Valley.

	Price-Elasticity of Irrigation Water				
Water Availability (%)	*East*	*Main*	*West*	*Groundwater*	*Average*
100	-	-	-	-	-
90	-0.47	-0.81	-0.51	-0.28	-0.50
80	-0.53	-0.90	-0.41	-0.30	-0.50
70	-0.62	-1.11	-0.48	-0.34	-0.56
60	-0.75	-1.48	-0.59	-0.39	-0.66

About 83% of the water delivered for irrigation in the Mexicali Valley was used as input data for this model. If regional shadow values are assumed to be the same for the rest 17% of the water delivered in the ID 014, it is possible to extrapolate results for all of ID014.

2.7 Model Limitations

Limitations of this study arise from the model itself and from the data available. Economics of production literature offers a wide arrange of considerations. These can include but are not limited to time stand, aggregation, uncertainty, available technology, community characteristics and external shocks. For the last three, this model implies some level of homogeneity, not entirely unreasonable for the Mexicali Valley with mostly commercial agriculture and well developed markets for products and production factors.

For the time stand, this model is more concerned with the long term. Some authors argue that in the short run water use should be less responsive to costs (Gibbons 1986). In the long run, the farmer has more choices for using water more efficiently if water costs increase. Nevertheless, this assumption in the model is reasonable considering projections are for year 2020.

Disaggregated production models are usually more time and data demanding; however, they have proved to be effective in modeling with higher precision policy changes in some rural economies (Taylor *et al.* 2005). Applications of production behavior with high levels of disaggregation for water use include Howitt and Msangi (2006) and for village economies in Mexico Dyer (2002). Where production conditions are more homogeneous and relatively stable, disaggregation is less valuable. One application where highly aggregated and disaggregated models interact and show important gains in information is Dyer *et al.* (2006). The level of disaggregation in the model in this study falls within a middle range. The underlying assumption is that farmers within an irrigation module behave about the same. Although there will always be small and large agricultural production units the Mexicali Valley is far from extremes such as subsistence agriculture. Thus this assumption in the model is at least partially justified.

For the regional model which has four module groups, the underlying assumption is that water is transferable within the module group but not outside of the group. This second restriction is more unrealistic for contiguous module groups. Nevertheless grouping by both geographical and land quality (and therefore yield) considerations may overcome this limitation at least partially.

Uncertainty from weather and prices also influences cropping decisions. Weather is a fundamental factor for both rainfed and irrigated agriculture. Relatively stable weather in a purely irrigated region will overcome some uncertainty in production. Government programs guaranteeing a price for some crops can reduce producer surplus fluctuations seen by the farmer.

Finally, data limitations on production costs may impose a challenge to water shadow value estimates, as average costs for the Mexicali Valley are used. This is not a problem for costs that remain more or less static and homogeneous for all users such as water and labor costs. Land rental prices are addressed based land quality characteristics. Nevertheless, supplies and resource usage may vary from farmer to farmer depending on particular characteristics of the production units. This concern can be addressed as more data becomes available.

2.8 Conclusions

Valuation of irrigation water has inspired numerous volumes of literature. This chapter offers a method to estimate water value for irrigation with minimum datasets. The Mexicali valley is an excellent laboratory for estimating value of water given the absence of rainfed agriculture, a pervasive flat topography, a high proportion of high quality soils, and a lower bound for water availability. The ratio of shadow value of water to water fee for current water supply conditions ranges from 2.7 to 5.9. The estimated average price-elasticity of water in the Mexicali Valley ranges from -0.5 to -0.67. Results also reveal that low-value crops and poor-land quality agricultural regions are the likely sellers of water under extreme scarcity conditions. Improvements to the estimation include incorporation of better empirical crop price response in the Mexicali Valley.

Crop prices will heavily influence water value for irrigation and consequently price elasticities as discussed by some authors (Gibbons 1986). A similar case occurs for heterogeneity on yields and/or irrigation efficiency. On-site and at source valuation of water are also different. Finally, results using mathematical programming techniques call for caution on interpretation of results, as some hidden costs might increase water shadow values. Thus estimations from this study can be taken as a solid upper bound for irrigation water value in the Mexicali Valley. These results provide an insightful means to create penalties for the regional economic-engineering optimization model of the Baja region discussed in the next chapter.

Chapter 3 Urban Demand Model for the Mexicali Valley

3.1 Introduction

In this chapter an urban water demand model for the Mexicali Valley is proposed and estimated. The main purpose of this section is to estimate the value of water deliveries for urban users at projected 2020 population levels. Inductive techniques using econometrics for aggregated consumption datasets are used. Residential and an amalgam of industrial, government and commercial uses are included. Time series data from municipal utilities are used. The cities of Mexicali and San Luis Rio Colorado are used as a case study.

The second largest users of water in the Mexicali Valley are the border cities of Mexicali and San Luis Rio Colorado. Nevertheless, the fast growing cities east of the valley, Tijuana, Tecate, Rosarito and Ensenada also claim water from the Colorado River via the Colorado River-Tijuana aqueduct. Whereas these eastern cities are not within the scope of this dissertation, nearly 100 MCM per year are taken from the valley for these urban uses.

This chapter is organized as follows. First, a literature survey for urban water valuation techniques is presented. Second, demand models for residential and non-residential uses are presented. A third section describes the study site and dataset. Results of the estimated demand models appear in the fourth section. Conclusions follow to summarize the main findings of this empirical exercise. Contributions of this study include the empirical estimation of aggregated urban water use response to water price in an arid developing region under two contrasting block rate price structures.

3.2 Literature Survey

Urban water uses can be further classified into two broad subgroups; water as consumer good and as a production input. For residential use, water is mostly a consumer good. However for agriculture and industry, water is considered a production input. In between are commercial and government (institutional) water demands, in which water is used for conducting business although it is partially devoted to human consumer uses (*e.g.* drinking, bathing and cooling). This section surveys literature on valuation of water for residential and non-residential uses. Both applications seek to estimate price-elasticity of demand, for obtaining marginal valuation of the resource among users. Brief remarks on commercial and institutional use are offered.

In this study water is grouped into two broad uses, residential and non-residential. Government and Commercial uses are combined with the industrial sector as *non-residential* water uses.

3.2.1 Residential demand

As with modeling of agricultural water demands, there are two broad families of models for valuing residential water uses, namely deductive and inductive methods. For more deductive methods, mathematical programming has been used to estimate willingness to pay to avoid residential water shortages with probabilistic shortages (Lund 1995). Using a similar approach Garcia-Alcubilla and Lund (2006) incorporated heterogeneity in household characteristics via Monte Carlo simulations. These approaches are useful for estimating and understanding willingness to pay for residential water supply reliability. Inductive techniques using econometrics correspond to the second family of methods. These methods prevail in residential water demand literature, and are suitable to estimate water demand price-responses when a uniform distribution of shortages is assumed. This is the case of the present study.

Econometric techniques for estimating water price-elasticity with increasing block rate structures have been in the economic literature since the early 1960s. Espey *et al.* (1997) offer one of the most recent meta-analysis of price-elasticity of residential demand. Elasticity estimates seem sensitive (at a 5% significance level) to model specification, evapotranspiration, seasonal controls, rainfall and temperature, and the use of a *difference variable* (Espey *et al.* 1997). Gottlieb (1963) is among the first studies on urban domestic water demand using utility cross-section data from Kansas. That work highlighted the importance of price and operating costs among the different utilities in the state. Nevertheless, Gottlieb's double-log model does not seem to control for variables such as marginal price per block rate and seasonality, as annual average per capita consumption is used to estimate elasticities. Despite its shortcomings, his price elasticity estimates fall within the typical range of estimates in urban demand literature.

More sophisticated demand models were developed in the 1970's, using time series analysis (*e.g.* Young 1973), and controlling consumption for several factors including temperature, seasonality (Foster and Beattie 1981, Griffin and Chang 1991), income and other implicit characteristics. Intra-household responses to price have been also addressed. Outdoor use (Howe and Linaweaver 1967) and summer consumption (Grima 1972) are more price elastic than indoor and winter consumption.

Billings and Agthe (1980) were among the pioneers in modern urban residential demand econometric specifications for block rate structures. They took insights from Taylor (1975) and Nordin (1976) in the sense that price becomes an endogenous variable under block rate pricing structures. They proposed one of the explanatory variables to be the difference between the water bill and what it would be paid if consumption is rated at the marginal price. Billings and Agthe are critical of the use of an average price in estimating elasticities since average price is ultimately determined by the quantity consumed thus introducing simultaneity issues.

A big dilemma in residential water demand literature is the use of an average versus a marginal price for the price-elasticity estimation. Average price is the ratio of total amount paid to the total water consumption. Marginal price on the other hand is the price paid at the last block rate. Technically, these prices are equal only in the case of a flat rate. More controversial is the study of Wong (1972),which found that price had a non-significant influence on water consumption in northern Illinois.

Young used average pricing in his 1973 study for Tucson, Arizona. He found average price was preferable for decreasing block rate price structures. More recently, Foster and

Beattie (1981) argue that consumers do not respond to a marginal rate, challenging the underlying assumption of a *perfectly informed* consumer. They compared their elasticity estimates using average price with the traditional Taylor-Nordin specification used in other studies (*e.g.* Billings and Agthe 1980, Griffin and Chang 1991). Foster and Beattie found that the hypothesis of equal coefficients (from average vs. marginal price specifications) could not be rejected at 10% significance. They argue that average price is superior (in terms of R^2) when only aggregate data are available. In a later work, Agthe and Billings (1986) recognize a simultaneity bias in their 1980 study, and proposed a simultaneous equation system to re-estimate. In this later study, they found significantly higher price-elasticities than in the allegedly biased 1980 model (respectively -0.624 vs. -0.49,), supporting the presence of simultaneity bias in Billings and Aghte (1980) study.

Howe and Linaweaver (1967) were among the first advocates of marginal price. They argued that household decisions on additional water consumption are based on the price of the last block rate, thus marginal price should be used to estimate price response. Gibbs (1978) argues that average price may lead to overestimation of elasticity, as he found predicted consumption varied from 22 to 107% between average and marginal price models.

A more recent application of water demand analysis using aggregate data was offered by Schefter and David (1985). They maintain Nordin's hypothesis on the difference variable and income coefficient being equal in magnitude and opposite in sign. They also highlight the importance of accounting for household heterogeneity in consumption and conduct a sensitivity analysis under four hypothetical probability distributions for consumption for their sample. Schefter and David found it was critical to know more about the proportion of users for each block rate, when aggregated data are being used. Nevertheless, Martinez-Espiñeira (2003) used a slightly better aggregate data set with numbers of users per block rate for three cities in Northeastern Spain. He found that weighting marginal price and Nordin's difference variable with the number of users per block rate makes little difference in elasticity estimates. In his study, Nordin's income-difference variable hypothesis is rejected as the absolute value of the coefficients differs by several orders of magnitude. One caveat on the Martinez-Espiñeira's dataset is the lack of variation in income, which he recognizes as a possible cause of non-significance of income and price difference coefficients. Since theoretically correct weighting of the marginal price and difference variable was used, the Schefter and David critique would not apply.

Nieswiadomy and Molina (1989), used Taylor-Nordin approach including an initial flat rate, and increasing and decreasing block rates. They included a proxy for income in their model based on mortgage payment and land value in Denton, Texas. The estimation technique of two-stage least squares and instrumental variables was argued to take care of the simultaneity issues of this model. Their elasticities fall within a typical range in the literature (-0.36 to -0.86). Nevertheless, they concluded that magnitudes of the difference variable and income are not equal with opposite sign, unsupportive of Nordin's hypothesis. One explanation for this finding is that water cost is a very small fraction of household income.

One of the most comprehensive approaches for elasticity estimation was developed by Hewitt and Hanemann (1995). They used the dataset from Nieswiadomy and Molina (1989) to estimate price and income elasticity of demand in a two-step fashion. In the first step, Hewitt and Hanemann defined a discrete choice model to predict the block of consumption a household would fall. A set of explanatory variables is used to estimate the probability distribution of the block rates. In the second step, demand is predicted as a function of the household characteristics, the weather, marginal price and a composite of difference variable (Nordin) and income. Their marginal price elasticity estimates are in the high-elastic range (-1.57 to -1.6).

Although, marginal price with difference variables seem to dominate the literature (Espey *et al.* 1997), there are some circumstances in which average price will favor a negative-sloped demand function. This is the case of decreasing block rates in which water is priced lower, with increased consumption thus driving average price down.

An additional issue often omitted in residential water demand analysis is the effect of demand side policies (DSM) or *non-price* policies. Renwick and Green (2000), using data on eight municipal water services found that DMS policies indeed have an influence on the aggregate of water consumed, and can be more effective than modest marginal price increments, under DMS policies such as water rationing and use restrictions. The authors argue that omission of DMS effect may lead to overestimation of residential water demand price responsiveness. Nonetheless, they recognize estimations may improve as information on household characteristics becomes available.

3.3 Model and Empirical Application

The main objective of this study is to estimate price elasticity for two contrasting block rate structures. In the first case, an increasing rate with an initial flat rate is used. The second rate structure has also an initial flat rate but a constant marginal price at each block rate. The design of these estimation models follows from data availability for a particular study site. For the increasing block rate structure, data are available on monthly consumption, rates and number of users per block rate. For the second location only total number of users is available.

The proposed econometric model is a hybrid of Billings and Agthe (1980) and Nieswiadomy and Molina (1989). From the first specification, this model takes the quantity demanded (per user), the marginal price, the difference variable, income and seasonal variables. From the second specification, an instrumental variable regression is used to overcome simultaneity issues.

As noticed by Taylor (1975), a residential water consumer has a non-convex budget constraint since different consumption levels lead to different rates. If water and all-other-goods are the only two inputs, the budget constraint would only be a straight line in the case of constant marginal prices. For other cases, this constraint is a kinked (segmented) line. Non-convexity in the budget constraint leads to multiple solutions or sudden solution-jumps.

In this model, water consumed per meter is a proxy for household consumption. Water consumed by the average household (*Q*) is assumed to be a function of the price in the last block rate (marginal price, *P*); Nordin's *difference* variable *D* as defined by Schefter and David (1985); an income variable *Y,* a seasonal dummy variable *W,* average monthly reference evapotranspiration, *ET* and monthly precipitation, *R.*

$$Q = f(P, D, Y, ET, R, W) \qquad (3.1)$$

And the regression equation is:

$$Q = \beta_o + \beta_1 P + \beta_2 D + \beta_3 Y + \beta_4 ET + \beta_5 R + \delta W + u \qquad (3.2)$$

where *u* is the error term and *W* is a vector of dummy variables for three out of four quarters in the year.

The marginal Price *P,* and difference variable *D*, are instrumental variables in the regression following 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 identifying the month Thus, the specified econometric models for marginal price and the difference variable are:

$$P = \lambda_o + \lambda_1 BR + \lambda_2 FY + \lambda_3 MON + v_p \qquad (3.3)$$

$$D = \gamma_o + \gamma_1 BR + \gamma_2 FY + \gamma_3 MON + v_d \qquad (3.4)$$

Where, BR stands for block rate identification (1-12), FY is the fiscal year (1-6), and QTR is a vector of dummies for the last three quarters of the year.

3.3.1 Variable Construction

Average household consumption Q_t for time step *t,* is the total water consumption at each block rate q_{rt}, divided by the number users in that block. The resulting number is then weighted by the number of users and added up across all consumption blocks and divided by the total number of users for all blocks at time *t.*

$$Q_t = \sum_r q_{rt} N_{rt} \Big/ \sum_r N_{rt} \qquad (3.5)$$

Where q_{rt} is total consumption in month *t* in block *r,* and N_{rt} is the number of users at block *r* and month *t.*

Marginal price P_t for the t-th time period corresponds to the marginal rate into which the average user falls. When a flat rate exists for an initial amount of water, the marginal price is zero. Marginal prices in the econometric equations above are deflated to a base year. The coefficient in marginal price is expected to be negative, as water is considered a normal good.

$$P_t = \sum_r P_{rt} d_{rt} \qquad (3.6)$$

where d_{rt} is 1 when r is the block of the average consumer in time step *t,* and 0 otherwise.

The construction of Nordin's price-difference variable (D-var) is inconsistent in the literature on water demand estimation. When a flat rate is present this procedure becomes more complex. In principle, Nordin (1976) proposed D-var to be the difference between the *actual* water bill and what this bill would be if all consumption is charged at the marginal price. For a flat rate there is a call of judgment on whether the bill at the marginal rate should include the first block or not. In other words, shall the total volume be multiplied by the marginal rate or just the amount below the flat-rate volume? One formulation for the price-difference variable D_{rt} was proposed by Niesmiadowy and Molina (1989) :

$$D_{rt} = \sum_{k=2}^{j} q_{k-1}\left(p_{k-1,t} - p_{kt}\right) + Flat_t \qquad (3.7)$$

$$D_t = \sum_{r} D_{rt} d_{rt} \qquad (3.8)$$

Price difference within contiguous blocks p_{k-1} and p_k is multiplied by the upper limit of the k-1 block. Difference variable D_t is the result of the dot product of D_{rt} and the dummy for block rate d_{rt} as defined above. This variable is expected to have a negative effect on water consumption, since the *subsidy* perceived by the consumer decreases as a user moves to a higher block rate.

An income variable *Y* is included. The state's gross domestic product per capita is proposed as a proxy for income. Climatic effects in the estimation include reference evapotranspiration *ET,* along with precipitation *R.* Seasonality is captured by a vector of quarter dummy variables *W*.

Average price was not used in this regression analysis. Besides simultaneity issues, marginal price has been advocated as the theoretically correct operationalization of price (Gibbs 1978). Additionally, Gibbs argues that difference in magnitude between marginal and average price at blocks other than the flat rate block is not significant (Figure 3-1). Other functional forms for obtaining elasticities, such as the Almost Ideal Demand System (Deaton and Muellbauer 1980), seem less suitable for estimation, since water consumption does not offer close substitutes.

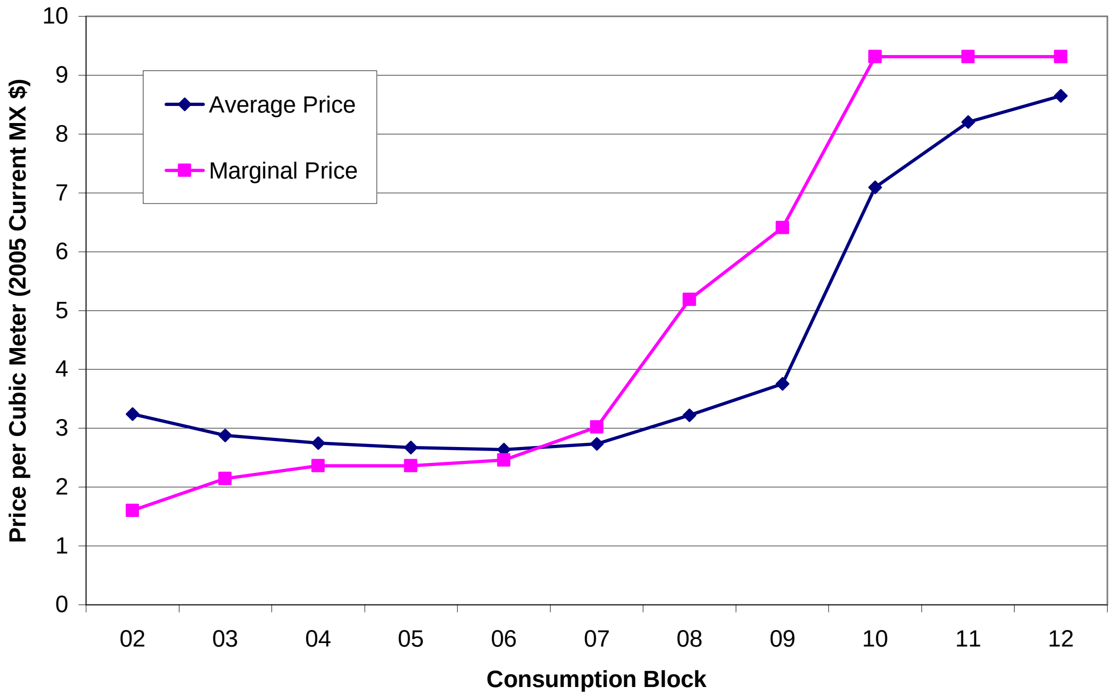

Figure 3-1 Price per cubic meter in Mexicali (Source: CESPM 2006)

3.3.2 Non-Residential Uses

In this study, non-residential uses (commerce, government and industry) are assumed to be inelastic. This faces the unrealistic assumption that commercial uses are unrresponsive to prices and the more realistic one that government is not price-responsive. On the other hand, according to Young (2005), empirical evidence suggests that the contribution of water to industrial end-products is minor compared to capital and other production inputs. He argues the small number of studies conclude industrial water use is price-inelastic.

Penalty functions for urban scarcity are obtained from numerical integration of a water demand curve, following the methods in Jenkins *et al.* (2003), and Gibbons (1986). The procedure is detailed in the Appendix 3

Methodological and empirical innovations of this approach include the use of instrumental variable regressions following Nieswiadomy and Molina (1989) contrasting different increasing versus constant rate structures. In addition, actual distribution of users per block rate is used to weight marginal price and difference variables, avoiding distribution assumptions (*e.g.* Schefter and David 1985).

The hybrid model of this study presents a fair balance between data availability and econometric representation of residential water use. A dataset richer in household demographics (*e.g.* Hewitt and Hanemann 1995) would deserve a model that includes individual household characteristics and not *average-user* ones. Nevertheless, this dataset was not available at the time of this study. As discussed before the specification of

Billings and Agthe (1980) did not explicitly address simultaneity issues. Nieswiadomy and Molina (1989) offer an instrumental variable approach suitable for aggregated data, that overcomes simultaneity bias. The inclusion of DMS policies in the analysis (see Renwick and Green 2000) might add less value when datasets include only few water agencies.

3.4 Case Study and Data

3.4.1 Urban Centers in the Colorado River Delta

The municipality of Mexicali is located in the Mexico-US border of Baja California. The last population and household census in 2005, indicates a total population of 855,962 with a population growth rate of 2.0% and 218,912 households (INEGI 2005). The city is surrounded by Irrigation District 014, Rio Colorado. Average household income in Mexicali is usually higher than the national average. For the ENIGH 2004 sample, weighted monthly household income for the municipality was 1.15 times national average (INEGI 2002, 2004).

San Luis Río Colorado is on the northwest Mexico-US border of the Mexican state of Sonora. Population in the municipality is 157,076 with 39,997 households (INEGI 2005).The city was founded in the last quarter of the 19th century as agriculture flourished in the Mexicali Valley. No information on per capita or household income for San Luis Río Colorado was available.

Data sources for residential water use in Mexicali include statistics from the *Comisión Estatal de Servicios Públicos de Mexicali* (CESPM) and the I*nstituto Nacional de Estadística, Geografía, e Informática* (INEGI). Water consumption data from CESPM is a balanced panel of 72 months of consumption from January 2000 through December 2005. Consumption is disaggregated into 15 price blocks. For each consumption block, there is information on total consumption in cubic meters, number of customers, and total revenues. Price at each block is also a time series of 72 months (*i.e.* price changes every month for each block). Consumption of the average household is approximated by weighting per customer consumption at each block rate by the number of customers per block. Income information for households in Mexicali and San Luis Rio Colorado comes from the National Income-Expenditures Surveys (ENIGH) for years 2000, 2002 and 2004. Currency in the analysis is set at 2002 pesos using the Mexican Central Bank's Consumer Price Index.

Both Mexicali and San Luis Río Colorado are in CNA Hydrological Region 7 (Río Colorado), characterized by a low average (1941-2002) rainfall of 130.3 mm/year (CNA 2004) and extremely high temperatures. For Mexicali, water is provided by the *Comisión Estatal de Servicios Públicos de Mexicali* (CESPM), who claims to supply 84% of the municipality (98% of the city) with 245,214 residential customers in 2005 (CESPM 2006). This figure contrasts with INEGI's number of households for the municipality. Growth rate of residential customers has been about half a percent point in the last 6 years. One possible reason for this discrepancy is that businesses might illicitly report themselves as residential customers to get a better tariff. 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). The utility reports 53,084 residential customers (of 55,830) for 2005. Near 2000 new residential customers (~4%) have been added every year in the last six years (OOMAPAS 2006). As with Mexicali, there are more customers than households. The average household size in both municipalities is about 3.91 members.

Water in urban centers in the CRD is mostly for residential consumption as shown in Table 3-1. In the case of Mexicali yearly average consumption (2000-2005) is 75% for residential customers, compared to 10% for commercial, 8 % for industrial, 9% for government (CESPM 2006). For San Luis Rio Colorado, residential consumption is even more significant in terms of total consumption (89%).

Table 3-1 Average (2002-2005) urban water use in the Colorado River.

Use Cases	***Mexicali*** Consumption (1000 m3/yr)	Share (%)	***San Luis Río Colorado*** Consumption (1000 m3/yr)	Share (%)
Residential	56,681	73%	31,715	89%
Commercial	6,936	9%	2,055	6%
Industrial	6,498	8%	1,933	5%
Other	7,453	10%	N/A	N/A
Total	77,568	100%	35,703	100%

Source: CESPM (2006) and OOMAPAS (2006).

Using CESPM consumption data, weighted-average consumption in the city of Mexicali is around 20 cubic meters per month per household. The ENIGH (2002 and 2004) data sets contain total expenditures in water for the surveyed households (n=258). For each household these expenditures were converted into cubic meters consumed per month. The estimated average was 30.9 cubic meters per household per month. Nevertheless the period of reference for these expenditures is summer. CESPM data for summer months (*e.g.* June-August) averages 24.8 cubic meters per household, about 80% of ENIGH's figure.

Consumption data for Mexicali is a balanced panel of 72 months of consumption from January 2000 to December 2005. Consumption is disaggregated into 15 price blocks. For each consumption block there is information on total consumption in cubic meters, number of customers, and total revenue per block. Price at each block is also a time series of 72 months (*i.e.* price changes every month for each block). Consumption of the average household is approximated by weighting per customer consumption at each block rate by the number of customers per block as described above. Unfortunately, household income information in Mexicali and San Luis Rio Colorado is not available for the entire time span (2000-2006). At best information from the National Income-Expenditure Household Survey (ENIGH) for years 2000, 2002 and 2004 is available. Currency in the analysis is set at 2002 pesos using the Mexican Central Bank's General Consumer Price Index (IPC).

San Luis Rio Colorado data from OOMAPAS includes 72 months from January 2000 to December 2005. Although consumption is disaggregated per block rate, the number of customers at each block rate is more limited. Six-year-average monthly consumption per customer is around 41.6 m^3 per month. This amount doubles CESPM average per user consumption. Perhaps because it is not possible to weight this average with number of users per block. Unfortunately, ENIGH did not include surveys for the municipality of San Luis Rio Colorado, thus household level data for comparison is not available.

Historically, budget share in water has been a relatively small portion of total household monetary expenditures. Unless data for a residential demand study comes from household surveys, income information at a household level has been typically unavailable. From ENIGH sample (INEGI 2004), household budget share for water in Mexicali ranged from 0.016% to 9.5% of total monetary expenditures, with a weighted average of 1.5%. National average budget share for the same time period was 1.79%. National budget share for water is 6.8% greater than in 2000 but 8.4% less than in 2002. Thus it is safe to assume budget share increases very slowly and that Mexicali is slightly below the national average.

National budget share for water and income deciles maintain an inverse relationship. Figure 3-2 below depicts such a relationship, and it also makes evident that budget share across deciles remains relatively constant from 2000 to 2004.

Figure 3-2 National household budget share for water per income decile (INEGI, 2000, 2002, 2004).

As expected, average household consumption (and expenditures) increases with quarterly income decile Figure 3-3. Rate structure for residential water use in Mexicali is an increasing block with a flat rate for the first 5 cubic meters. Consumption ranges, and prices per block are shown in Table 3-2 for 12 out of the 15 blocks.

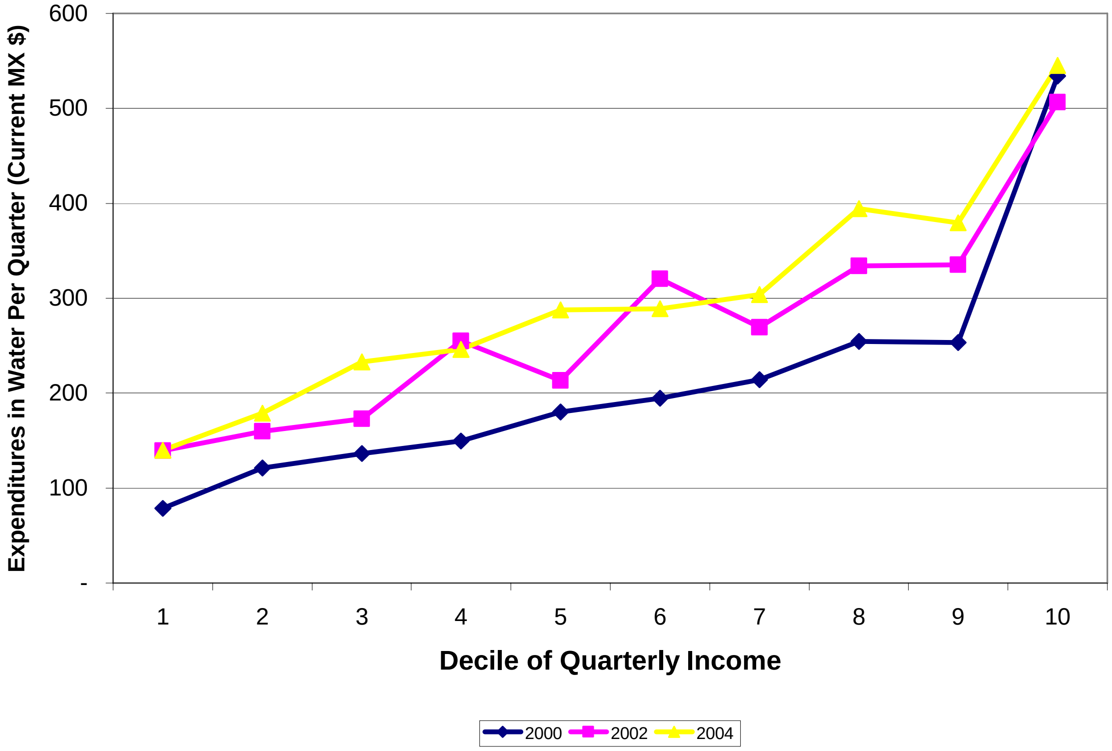

Figure 3-3 National quarterly household expenditures in water per income decile (INEGI, 2000, 2002, 2004).

Table 3-2 Water price structure for residential us in the city of Mexicali (CESPM 2006).

Block	Limits (m^3)			Price (Current MX $ / m^3)					
Number	**Min**		**Max**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**
1	0	-	5*	16.75	20.42	25.38	16.97	20.61	25.54
2	5	-	10	1.00	1.33	1.66	1.01	1.34	1.67
3	10	-	15	1.39	1.80	2.23	1.41	1.82	2.24
4	15	-	20	1.53	1.98	2.46	1.55	2.00	2.48
5	20	-	25	1.53	1.98	2.46	1.55	2.00	2.48
6	25	-	30	1.59	2.06	2.56	1.61	2.08	2.58
7	30	-	40	1.95	2.52	3.14	1.98	2.54	3.16
8	40	-	50	3.38	4.35	5.40	3.43	4.39	5.43
9	50	-	60	4.17	5.37	6.67	4.23	5.42	6.71
10	60	-	150	6.05	7.80	9.69	6.13	7.87	9.75
11	150	-	300	6.05	7.80	9.69	6.13	7.87	9.75
12	300	-	500	6.05	7.80	9.69	6.13	7.87	9.75

* Flat rate range. Source: CESPM (2006).

Figure 3-4, shows the real (2002 MX Pesos) rate per block from 2000-2005. Since block 1 is the flat rate block (*i.e.*, it is not marginal price), this has been omitted in the graph. A step increase in the marginal price can be noticed after block 7 in Figure 3-4. However if the upper and lower bound of each block rate are averaged, a linear-log plot of marginal price vs. block yields a positive sloped straight line. Thus marginal price does not increase linearly with consumption.

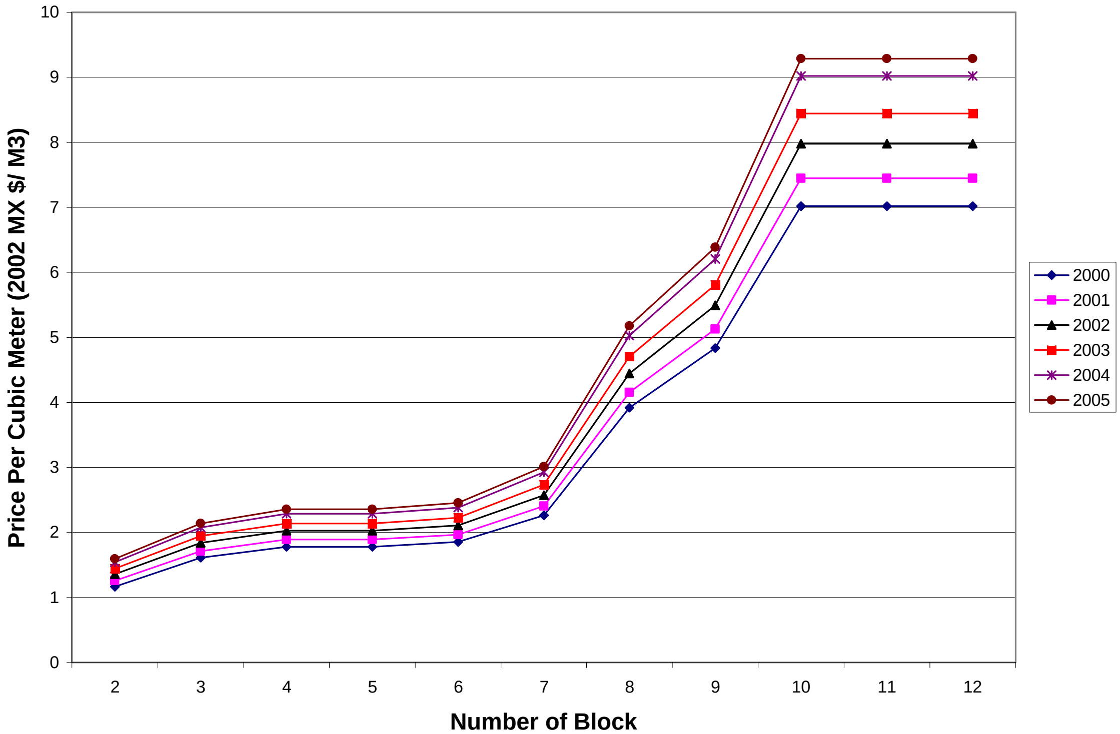

Figure 3-4 Price per cubic meter at each block rate in Mexicali (CESPM 2006).

Table 3-3 shows rate structure for the last six years for San Luis Rio Colorado. SLRC has simpler rate structure with a flat rate up to twenty cubic meters and a uniform rate for each extra cubic meter. Water has eight block rates for residential consumption. Nevertheless these blocks turn out to be irrelevant for residential use (albeit not for non-residential uses) since marginal price is uniform after 20 m^3. Unlike CESPM, the San Luis Rio Colorado Organism seems not to adjust water rates on a monthly basis. However, annual price adjustment in the last six years seems not to follow a well defined pattern since they range from 3.65% to 32.4% (*e.g.* adjusted for inflation).

Table 3-3 Water price structure for residential use in the city of San Luis Rio Colorado.

Block	Limits (m^3)			Price (Current MX $ / m^3)					
Number	Min		Max	2000	2001	2002	2003	2004	2005
1	0	-	20*	21.60	28.27	35.20	46.60	50.60	52.60
2	21	-	30	1.08	1.41	1.76	2.33	2.53	2.60
3	31	-	40	1.08	1.41	1.76	2.33	2.53	2.60
4	41	-	50	1.08	1.41	1.76	2.33	2.53	2.60
5	51	-	80	1.08	1.41	1.76	2.33	2.53	2.60
6	81	-	100	1.08	1.41	1.76	2.33	2.53	2.60
7	101	-	200	1.08	1.41	1.76	2.33	2.53	2.60
8	201	-	9,999	1.08	1.41	1.76	2.33	2.53	2.60

* Flat rate range. Source: OOMAPAS (2006).

Environmental data for this study includes precipitation and reference evapotranspiration (ETo) records. Since Mexicali and SLRC are both located in the Mexicali Valley, the same records were used in the corresponding estimations. Evapotranspiration data came from the California Irrigation Management Information System (CIMIS) database (Department of Water Resources 2006). Average monthly ETo in six sampling stations in the nearby of the Mexico-US border in Mexicali-Calexico (Imperial County) were used for this study. Monthly average rainfall (1941-2002) for hydrological region 7 comes from CNA's 2004 water statistics. Figure 3-5 shows the two climate variables above. Evapotranspiration is highest during the summer months, whereas precipitation is the lowest. Expected marginal effect on water consumption is positive for ETo and negative for rainfall.

Finally, seasonality is captured by quarterly dummy variables. Figure 3-6 below shows average monthly per customer consumption for Mexicali and SLRC. As expected, summer quarters have both the highest ETo and have the highest water consumption rates.

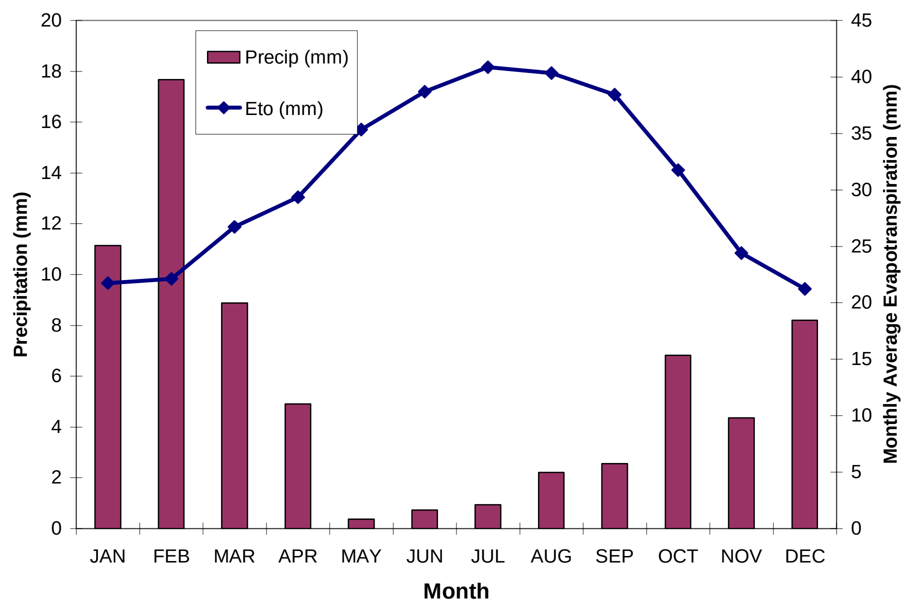

Figure 3-5 Monthly average total precipitation and reference evapotranspiration in the Mexicali Valley (Department of Water Resources 2006).

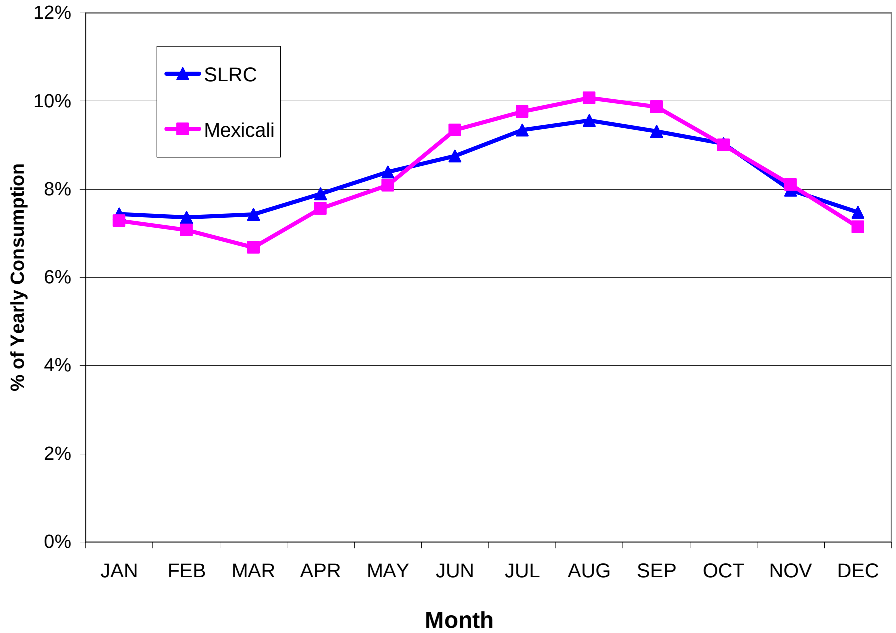

Figure 3-6 Monthly average (2000-2005) percent of annual residential water consumption for Mexicali and SLRC (CESPM 2006, OOMAPAS 2006).

Summary statistics for all variables in the regression appear in Table 3-4. The city of Mexicali shows smaller per customer consumption than SLRC. Customer income proxy (per capita state GDP) is slightly higher for Mexicali. On the other hand Mexicali has higher marginal price and difference variable. Climatic and seasonal data are the same for both locations.

Table 3-4 Summary statistics of variables in the regression model.

Mexicali

Variable	Description	Units	n	Mean	Std. Dev.	Min	Max
Qt	Monthly Avg. HH Demand	Cubic meters	72	22.94	3.78	15.72	31.62
Pt	Marginal Price	2002 MX Peso	72	2.12	0.20	1.76	2.40
Dt	Difference Variable	2002 MX Peso	72	-5.15	1.99	-16.49	-3.79
Eto	Reference Evapotransp.	Milimiters	72	30.92	7.56	19.75	42.40
Yt	State per Capita GDP	2002 000's MX Peso	72	75.37	3.59	70.04	79.69
R	Monthly Precipitation	Milimiters	72	5.73	6.95	0.00	35.81
M1-M4	Months Jan-Apr	Non-dimentional	72	0.33	0.47	0	1
M5-M8	Months May-Aug	Non-dimentional	72	0.33	0.47	0	1
M9-M12	Months Sep-Dec	Non-dimentional	72	0.33	0.47	0	1
Block	Rate Block Number	Non-dimentional	72	5.04	0.81	4	7
Year	Fiscal year	Non-dimentional	72	2.50	1.72	0	5
Month	Number of the Month	Non-dimentional	72	6.50	3.48	1	12

San Luis Rio Colorado

Variable	Description	Units	n	Mean	Std. Dev.	Min	Max
Qt	Monthly Avg. HH Demand	Cubic meters	72	46.58	5.32	36.14	57.16
Pt	Marginal Price	2002 MX Peso	72	1.87	0.43	1.16	2.35
Dt	Difference Variable	2002 MX Peso	72	-4.23	1.62	-7.43	-1.27
Eto	Reference Evapotransp.	Milimiters	72	30.92	7.56	19.75	42.40
Yt	State per Capita GDP	2002 000's MX Peso	72	72.95	4.61	65.20	78.28
R	Monthly Precipitation	Milimiters	72	5.73	6.95	0.00	35.81
M1-M4	Months Jan-Apr	Non-dimentional	72	0.33	0.47	0	1
M5-M8	Months May-Aug	Non-dimentional	72	0.33	0.47	0	1
M9-M12	Months Sep-Dec	Non-dimentional	72	0.33	0.47	0	1
Block	Rate Block Number	Non-dimentional	72	4.17	0.61	3	5
Year	Fiscal year	Non-dimentional	72	2.50	1.72	0	5
Month	Number of the Month	Non-dimentional	72	6.50	3.48	1	12

3.4.2 Non-Residential Water Data

As suggested before, estimation of the price elasticity for non-residential uses is not part of this study. However, data on consumption and block rate structure is presented below for year 2005 from statistics the corresponding water utilities. Residential and non-residential consumption patterns display similar seasonal behavior (Figure 3-7). Non-residential uses include industrial, commercial and government activities. For the city of Mexicali this represents roughly 27% of total consumption (average 2001-2005, CESPM 2006). Being a smaller city, non-residential uses in SLRC are only 11.2% of the total consumption (average 2000-2005, OOMAPAS 2006). Figure 3-7 depicts water consumption patterns for residential and non-residential uses in Mexicali. Similarly, Figure 3-8 shows monthly consumption patterns for SLRC. For both cases the non-residential and residential use varies similarly with season. Government uses in Mexicali show greater variation in consumption.

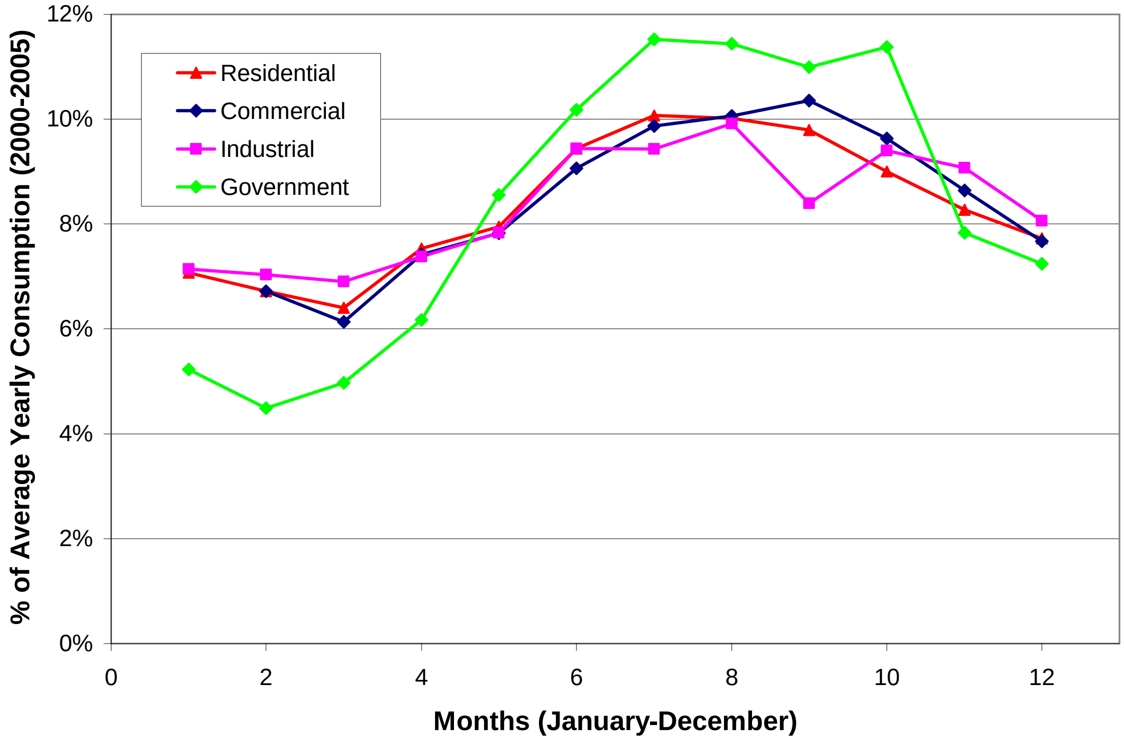

Figure 3-7 Monthly water consumption patterns by user in Mexicali (CESPM 2006).

On the supply side, water pricing for non-residential uses follows an increasing block rate structure for both locations. The number of non-residential users in 2005 for Mexicali was 17,856 and 2746 for SLRC. In SLRC, at all blocks non-residential water is sold at least 1.67 times the rate for residential.

Because non-residential water use in the Mexicali Valley follows residential consumption seasonal patterns, the aggregate response to water price in this study takes non-residential consumption as a fixed portion of total water demand.

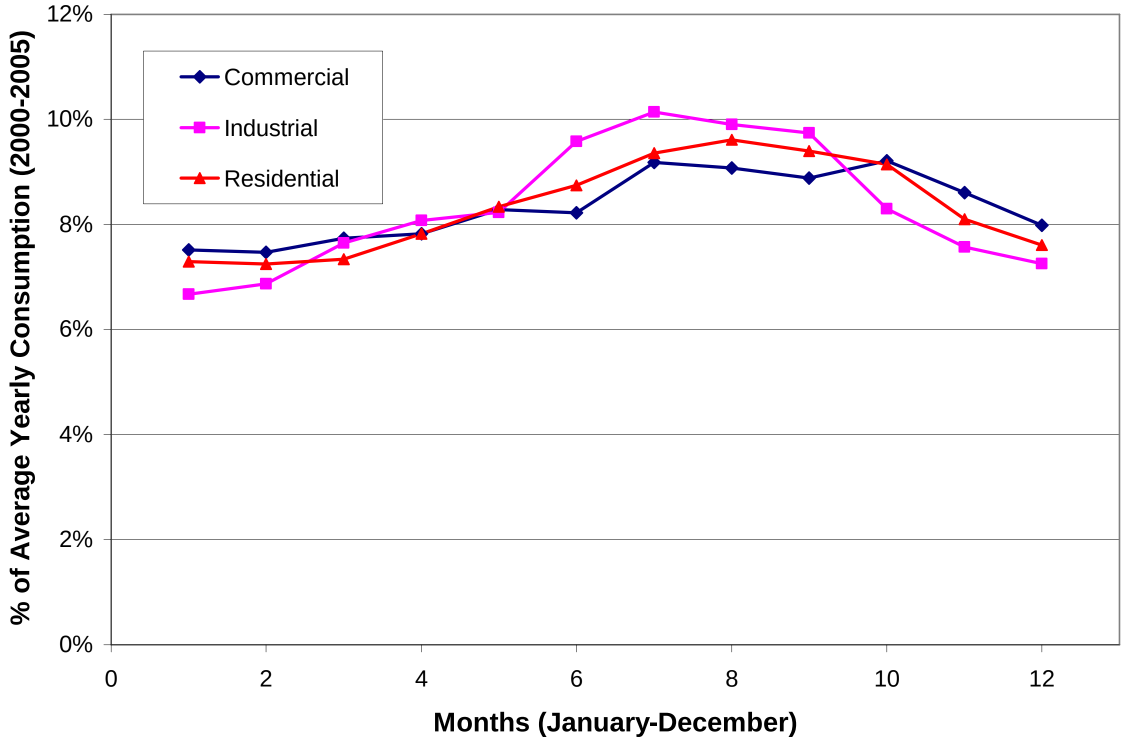

Figure 3-8 Monthly water consumption patterns by user in SLRC (OOMAPAS 2006).

3.5 Results

Instrumental variables regression was performed for Mexicali and SLRC data using 72 observations with STATA™. Block rate identification, year and seasonality binary variables were used as instruments for marginal price and difference variables in the first step. This configuration was used by Nieswiadomy and Molina (1989). The second step included the instrumented variables from the first step, evapotranspiration, per capita state gross domestic product (as proxy for income), and two out of three dummy variables for seasonality for winter and fall. Given the limited number of observations, statistical non-significance and possible issues of multicolinearity, additional variables were not introduced. Regression results are comparable to those found in the water demand literature for residential water demand studies in the US 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 (Table 3-5), price elasticity of demand at the mean levels of marginal price and per customer consumption is -0.76. Goodness to fit in terms of adjusted R-squared is 0.70. Results indicate that marginal price, difference variable, reference evapotranspiration and less warm months are statistically significant explanatory variables at a 0.01 level. Household income proxy and rainfall variables turned out to be non-significant. With the exception of the non-significant explanatory variables, regressors in the model had the expected sign.

Albeit non-significant, the income proxy coefficient has a negative sign. One possible explanation is that data for this parameter is varied annually and not monthly as the rest of the parameters. Another non-significant coefficient with an unexpected sign is rainfall. This coefficient is inversely correlated to reference evapotranspiration (r = -0.57), but apparently fails to explain water demand. Omitting these two explanatory variables does not substantially change results of the regression.

Table 3-5 Regression estimates for Mexicali.

Variable	**Model Formulation**			
	OLS	2SLS	*2 SLS First Stage*	
	Qt	*Qt*	*Pt*	*Dt*
Constant	**30.07**	**31.11**	***1.16***	***11.64***
	(7.40)	(5.10)	*(5.60)*	*(2.31)*
Marginal Price (Pt)	**-8.73**	**-8.20**	---	---
	-(9.90)	-(6.13)		
Difference Variable (Dt)	**-0.68**	**-1.49**	---	---
	-(7.08)	-(5.48)		
Reference Evapotranspiration (Eto)	**0.31**	**0.19**	*0.00*	*-0.01*
	(8.08)	(2.74)	*-(0.23)*	*-(0.13)*
Income (Yt)	-0.02	-0.05	*0.00*	*-0.05*
	-(0.46)	-(0.66)	*(0.75)*	*-(0.86)*
Rainfall (R)	0.02	0.02	*0.00*	*0.01*
	(0.67)	(0.37)	*-(0.88)*	*-(0.16)*
Months Jan-Apr (M1-M4)	**-1.57**	**-2.18**	*0.07*	***-1.76***
	-(2.43)	-(2.21)	*(1.57)*	*-(1.65)*
Months May-Aug (M5-M8)		**---**	---	---
		---	---	---
Months Sep-Dece (M9-M12)	0.83	-0.10	*-0.01*	*-0.01*
	(1.55)	-(0.11)	*-(0.22)*	*-(0.01)*
Consumption Block		**---**	***0.10***	***-4.62***
			(5.10)	*-(3.02)*
Year		**---**	***0.13***	***-0.36***
			(20.62)	*-(2.38)*
Month Number		**---**	*0.01*	*-0.13*
			(0.75)	*-(0.77)*
R2-adjusted	0.87	0.70	*0.89*	*0.70*
Price Elasticity	**-0.80**	**-0.76**	---	---
Income Elasticity	0.00	-0.16	---	---

*The number in parentheses is the t-ratio. Bold indicates significance at 0.05 level.

Estimations made using ordinary least squares (first column), does not make a significant difference in terms of marginal price coefficients (p-value > 0.10). Elasticity at the means is slightly higher and so are some other significant coefficients. Although goodness to fit would seem slightly better than the IV regression, OLS estimation would be less reliable since simultaneity issues may arise from the price variables as discussed above.

Results for SLRC (Table 3-6) are similar to those for Mexicali in terms of statistical significance and sign of the regression coefficients. SLRC does not have an increasing block rate structure after the flat rate consumption, thus it is expected to have lower price elasticity than Mexicali. This is the case for both OLS and Instrumental Variables regression analysis. At the means, price elasticity in SLRC was estimated in -0.62 which is reasonable since SLRC is a relatively small city with a constant rate price structure.

The construction of Nordin's difference variable in this case took into account the flat rate cubic meters. The justification for this specification is that intra-marginal price difference is null after the flat rate block, making the difference variable negligible. The coefficient on price difference variable is significant at a 0.01 level and inversely correlated with water consumption, as expected by Nordin (1976) and other studies using this variable.

Goodness to fit seems higher than that for the Mexicali regression analysis. In this case however, more explanatory power lies in the constant variable. This high goodness of fit (as R^2) value calls for some skepticism, as most studies where this value is reported are well below the 0.80 (Weber 1987, is an exception). Diagnostic tests including residual plots do not show a systematic pattern for the residuals in the estimations.

Table 3-6 Regression estimates for SLRC

Variable	**Model Formulation** OLS	2SLS	*2 SLS First Stage*	
	Qt	*Qt*	*Pt*	*Dt*
Constant	**56.27**	**53.21**	***1.43***	***4.53***
	(12.28)	(10.59)	*(3.09)*	*(2.05)*
Marginal Price (Pt)	**-12.54**	**-15.41**	---	---
	-(9.84)	-(9.93)		
Difference Variable (Dt)	**-2.99**	**-3.50**	---	---
	-(10.07)	-(9.36)		
Reference Evapotranspiration (Eto)	**0.22**	**0.17**	***-0.01***	*0.01*
	(4.29)	(2.89)	*-(2.88)*	*(0.57)*
Income (Yt)	-0.07	0.04	***0.04***	*0.01*
	-(0.96)	(0.48)	*-(3.21)*	*(0.48)*
Rainfall (R)	-0.01	-0.02	*-0.01*	*0.01*
	-(0.38)	-(0.66)	*-(0.88)*	*(1.91)*
Months Jan-Apr (M1-M4)	**-0.77**	**-0.67**	*0.01*	***-0.06***
	-(1.04)	-(0.87)	*(0.13)*	*-(0.18)*
Months May-Aug (M5-M8)		**---**	---	---
		---	---	---
Months Sep-Dece (M9-M12)	-0.43	-0.86	*-0.02*	*-0.20*
	-(0.65)	-(1.23)	*-(0.35)*	*-(0.63)*
Consumption Block		**---**	***0.15***	***-1.85***
			(3.90)	*-(10.36)*
Year		**---**	***0.28***	***-0.97***
			(15.57)	*-(11.46)*
Month Number		**---**	*-0.01*	*-0.01*
			-(0.81)	*-(0.14)*
R2-adjusted	0.91	0.90	*0.92*	*0.88*
Price Elasticity	**-0.50**	**-0.62**	---	---
Income Elasticity	-0.11	0.06	---	---

*The number in parentheses is the t-ratio. Bold indicates significance at 0.05 level.

Multicolinearity is also discarded as the values in correlation matrix of regressors do not exceed 0.80 in absolute value, as proposed by Judge *et al.* (1988).

One caveat of this study is that observations are an aggregate for each block rate; there is only information on the number of connections. Thus at best it can provide water delivered per connection. Some of these connections can be inactive. Nevertheless the data set allows elimination of users that pay a fixed rate independent of consumption. Leaks estimated at 13.7% in Mexicali, (CESPM 2006) and illegal connections would introduce some inaccuracy (Young 2005). Conveyance inefficiency has not been addressed to this author’s knowledge in residential water demand literature in Mexico.

Another issue is that of commercial efficiency, that is the fraction of the metered water that is actually billed. Nevertheless, CESPM argues its commercial efficiency is around 98% (CESPM 2006).

Aggregation issues have been addressed by Espey *et al.* (1997). They concluded that for their sample there was no significant difference between price elasticity estimates whether data was at a household level or a community aggregate.

Another limitation of aggregated data is the inability to account for multifamily dwellings. Administrations of some apartment buildings charge individual apartments a flat rate while receiving a block-rated bill from the utility. This could introduce some bias toward the lower range of the price elasticity estimate, as users could seem less responsive to price than they would be if charged directly by the utility.

Lastly, a remark about the construction of aggregated demand curves from price elasticity estimates in this study. Although non-residential uses follows the same seasonal pattern than residential use, price response can be under-estimated if non-residential uses are assumed have negligible price-elasticity. As noticed in the Appendix 3 , penalty functions are constructed to work in CALVIN. In the long run, a fixed block of non-residential consumption within the penalty function (or aggregate demand curve) will underestimate scarcity value of water since firms may adopt water-saving measures. However, this author assumes similar this would not be significant for the short run.

3.6 Conclusions and Policy Implications

As water become scarcer, public utilities in fast growing urban centers will adopt policy and operational measures to promote increased water use efficiency. Whereas conveyance efficiency might be mostly correlated to infrastructure investment and operation plans of the utility, household water consumption could become more driven by behavioral factors. A vast literature suggests that price is an important determinant of water consumption, even for the aggregate of users. The data seems to support the generalization that higher residential water expenditures most frequently involve households with higher levels of income. Thus water pricing policies aimed to impose fewer burdens at low levels of water consumption and household income should be pursued.

The cases studied in this research are not like those common in developing countries where water is often unmetered. In this study it was possible to use econometric techniques to estimate response to price, since the dataset contained detailed consumption information. A possible improvement would be to perform a sensitivity analysis where current results are compared to those where the number of users per block rate in SLRC is used. Furthermore, information on household income and its distribution would yield a better income variable.

Although household water expenditures in water for the cities of Mexicali and SLRC are only a small portion of total household expenditures, estimates of this study prove residential users are rather unresponsive to price changes. Some authors argue that the underlying assumption of a perfectly informed consumer is flawed. This study contrasts a complex and a very simple rate structure for residential consumption. Although users may face different levels of understanding of the rate structure and respond differently to it, findings show that aggregate price response is far from absent even under simpler rate structures. Furthermore, both the price levels and complexity in the rate structure are inversely correlated to the magnitude of such price response.

The research on urban water demand in developing countries should include specifications that maximize the use of available data on consumption and demographics. Since household level data on water consumption and demographics is often unavailable, specifications that use aggregate data may be more useful for future research on urban water demand and price response.

Chapter 4 Systems Analysis for Environmental Water Flows in the Colorado River Delta.

4.1 Introduction

In this chapter an economic-engineering optimization model is used to explore potential water supplies for environmental restoration of the Colorado River Delta, Mexico. Potential sources of water considered in the model include reductions in local agricultural and urban water uses increased operational efficiencies and wastewater reuse in Mexico and additional Colorado River flows from the United States. Water scarcity and operating costs, water scarcity volumes, marginal economic costs of environmental flows, and marginal economic values of additional Colorado River flows from the United States are estimated using the model for several institutional and infrastructure alternatives over a wide range of required delta environmental flows. The results provide insights into economically promising sources of water supplies for restoration activities, including infrastructure and institutional activities within Mexico and in coordination with US water management.

Results indicate that wastewater reuse would provide only a small environmental water supply and the economic desirability of additional Colorado River flows from the US is generally less than that of water transfers and operational changes in the Mexicali Valley. By quantifying the trade-off between agricultural and urban economic valuation and environmental flows, the results also provide a framework for decision-makers to quantify their value of environmental flows. The model also provides a framework for integrating more specific knowledge of the hydro-economic system as this information becomes available.

This chapter is organized as follows. A brief literature review of systems analysis is followed by a description of the modeling approach. The empirical application using systems analysis for the Colorado River Delta is then described in detail. Water management alternatives are the focus of the fourth section. Results of implementing the water management alternatives are presented, then my conclusions.

4.2 Literature Survey

4.2.1 Systems Analysis and Economics

Systems analysis in water resources is defined by Rogers and Fiering (1986) as “a set of mathematical planning and design techniques which includes at least some formal optimization procedure” (p. 146S). Hufschmidt and Fiering (1966) seminal book on simulation modeling, provides applications of cost-benefit analysis to hydrologic systems. The U.S. Water Resources Council (1983), provides a six-step procedure for applying systems analysis for planning and evaluation of water projects. Systems analysis applied to hydro-economic models Harou and Lund (In Press) identify Bear and Levin (1970) and Gisser and Mercado (1972, 1973) among the first attempts to connect water value functions with hydrology and water infrastructure to elicit promising water management strategies. More recent contributions discussed in Chapter 1 of this dissertation include Booker and Young (1994), Vaux and Howitt (1984), Diaz and Brown (1997), in which benefit functions of water use have been embedded in a hydrologic system to meet specific performance objectives. Cai *et al.* (2003)used domain decomposition in large-scale hydro-economic modeling to accommodate an endogenous agricultural water demand model. These applications evidence the importance of including economic incentives in water resources analysis.

In optimization models for hydro-economic systems the researcher can either maximize benefits of water use or minimize costs of scarcity. Following Labadie (2004) optimization models fall at least within two broad categories: Implicit Stochastic Optimization (ISO) and Explicit Stochastic Optimization (ESO). For the first group, hydrology is either historical or synthetically generated and used (implicitly) in a deterministic optimization model. Linear programming, network flow optimization, non-linear programming, and discrete and differential dynamic programming models fall within this category. In ESO, models solve a program using probability distributions of random variables, usually streamflows. Chance constrained, stochastic linear and dynamic programming, stochastic optimal control, and multi-objective optimization are among the methods most commonly encountered in this category.

Network flow programming (NFP) is a form of linear programming, in which the decision variable is the *flow* through *links* of two or more inter-connected *nodes*. The constraint set of a NFP includes mass balance of flows in all nodes, as well as minimum and maximum flow capacity interconnecting links. The generalized version of NFP allows gains (or losses) within each link, at the expense of some extra computational effort. Applications of pure and generalized network flow programming include MODSIM (Labadie 1995) and Israel and Lund (1999) respectively.

4.2.2 Optimization versus Simulation Models

The typical analysis in water resources is through the use of simulation models. Labadie (1997) has regarded simulation models as descriptive, and useful in answering *what if* questions in a water system. Nevertheless, Labadie argues simulation models are less suitable for prescribing *best* system operation strategies, as are optimization models. Several authors have identified a gap between formulation and actual implementation of some optimization models in water resources management (*e.g.* Rogers and Fiering 1986, Labadie 1997). In the mid 1980's, Rogers and Fiering (1986) put in perspective the use of systems analysis, with a meta-analysis of surveys among professionals and institutions. They were aimed to answer the question of why it is that systems analysis and optimization models in particular had limited use in practice in developed and developing countries. Roger and Fiering (1986) suggest that "*models must harmonize with, i.e., be of the appropriate scale and complexity, not mere formally or mechanistically correct, the joint physical and institutional systems whose performance is to be modified.*" (p. 156S). Labadie (1997) on the other hand, suggests 1) lack of confidence in optimization, 2) hardware and software limitations, 3) results interpretation , 4) difficulty to incorporate risk and uncertainty among the most common deterrents for the use of optimization models.

Simulation and Optimization models are not necessarily exclusive. Lund and Ferreira (1996) in an application for the Missouri River, tested and refined results from their deterministic optimization model (HEC-PRM) using a mass balance simulation model. Thus in some instances, simulation and optimization models can interact and complement each other in designing strategies. “Simulation modeling is an essential companion for refinement and testing of *optimal* operating rules” (Lund and Ferreira 1996).

Systems analysis in water resources using linear programming offers several advantages over simulation models. First, linear programming models provide sensitivity information on the mass-balance and capacity constraints. Second, readily available and low-cost solvers are enough to execute model runs. Third, the formulation of the optimization program is relatively simple and its duality theory is well developed (Labadie 1997); thus it is possible to obtain sensitivity and other information from the LaGrange multipliers.

Application of large-scale water resources optimization models boomed in the 1990s, and Jenkins *et al.* (2001)offer several examples for the US and other countries. Among the applications for California are Lefkoff and Kendall (1996) who modeled the State Water Project and the Central Valley project and inquired on conveyance facilities expansions.

The systems analysis approach used in this dissertation was developed using a generalized network flow programming framework. This application departs from others (*e.g.* Diaz and Brown 1997, Cai *et al.* 2003) in several ways. First, the objective function is aimed to minimize total cost, which includes operation and scarcity costs. Most optimization models maximize benefits for particular uses including environmental uses. Second (and as a consequence), marginal willingness to pay for additional water is a marginal opportunity cost to other uses and not a marginal benefit from conservation measures. This is particularly beneficial since estimates of *environmental water* value on other uses in a basin may be non-existent or controversial (Shabman and Stephenson 2000). Third, shadow (dual) values on capacity constraints provide sensitivity information on worthwhile infrastructure expansions. Dual values reflect direct changes in the objective function as a result of relaxing conveyance or storage capacities in a system. The next section presents methodological details.

4.3 Modeling Approach

The hydro-economic optimization model employed for system analysis was built within the framework of the larger CALVIN model (Jenkins *et al.* 2001, Pulido-Velazquez *et al.* 2004). CALVIN is a systems analysis tool developed and successfully applied for strategic water management in California. In its earliest versions, four regions were comprised by this model in California, namely Sacramento and Bay Delta, Tulare Basin and Southern California (Figure 4-1). System representation includes 51 reservoirs, 28 groundwater basins, and 54 economically represented urban and agricultural demand areas, along with over 1250 links representing the State’s natural and built conveyance system. For the case of California, the overall objective of CALVIN is to minimize total water scarcity and operation costs given 72-years of hydrology (1921-1993).

CALVIN belongs to the category of generalized network flow optimization models (see Labadie 1997), where it is possible to account for losses and gains within node links. The model optimizes and integrates water operations and allocation based on costs and economic water scarcity for urban and agricultural users. CALVIN is an economic-engineering optimization model that explicitly integrates operation of water facilities, resources and demands for California's intertied system (Pulido-Velazquez *et al.* 2004). CALVIN uses HEC-PRM, a network flow optimization solver developed by the U.S. Army Corps of Engineers.

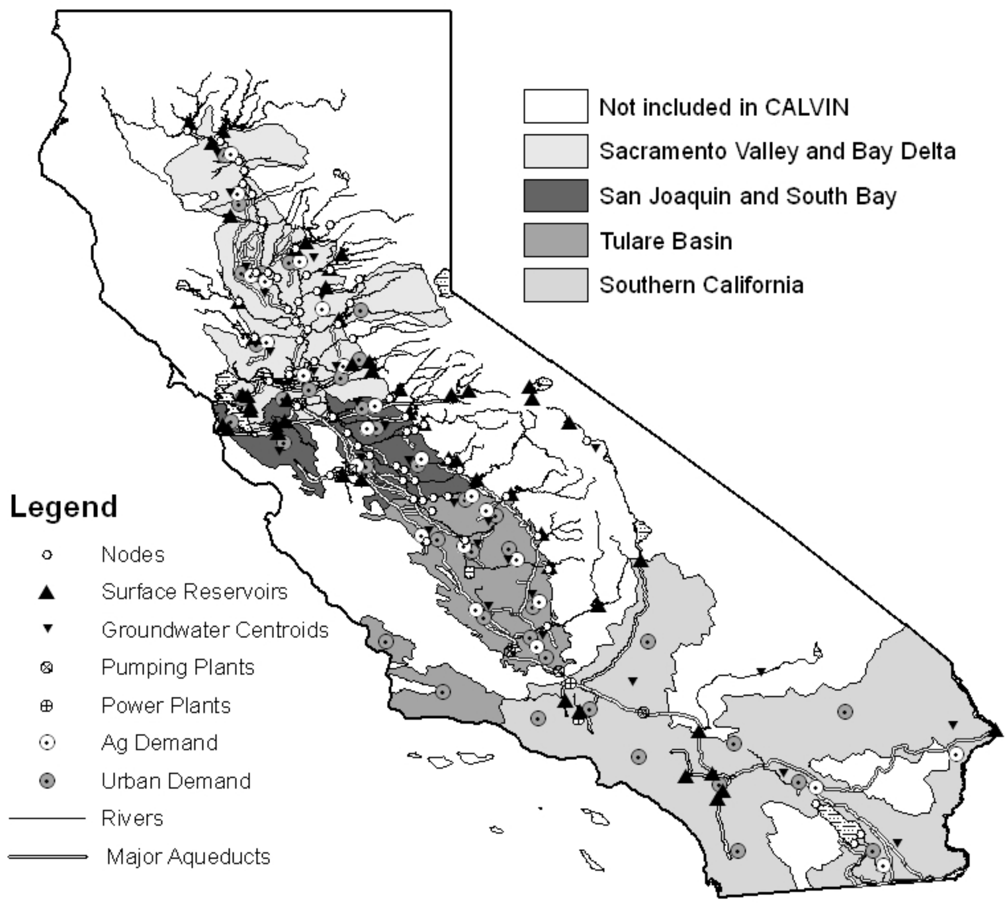

Figure 4-1 Hydrologic basins, demand areas, major inflows and facilities in CALVIN (adapted from Jenkins *et al.* 2001).

CALVIN results go beyond simple cost-benefit analysis by using the economic value of water for different users and supply costs to develop economically promising combinations of water management activities from a broad array of options including system re-operation, conjunctive use, water reuse and desalination, water markets, and reductions in water use. The CALVIN model has been applied to various water policy and management problems including climate change impact and adaptation studies (Jenkins *et al.* 2001, Lund *et al.* 2003, Jenkins *et al.* 2004, Pulido-Velazquez *et al.* 2004, Harou *et al.* 2006, Medellin-Azuara *et al.* 2006, Null and Lund 2006, Tanaka *et al.* 2006, Harou and Lund In Press).

The CALVIN model uses network flow optimization to find the minimum-cost systemwide operation and water allocation. The HEC-PRM generalized network flow optimization model for reservoirs is used to minimize the total cost of the entire network by solving the following set of equations:

$$Min_{X \geq 0} Z = \sum_i \sum_j c_{ij} X_{ij} \qquad (4.1)$$

$$\sum_i X_{ji} = \sum_i a_{ij} X_{ij} + b_{j,} \forall j \qquad (4.2)$$

$$X_{ij} \leq u_{ij} \quad \forall i, j \qquad (4.3)$$

$$X_{ij} \geq l_{ij} \quad \forall i, j \qquad (4.4)$$

where Z is the total cost of flows throughout the network, X_{ij} is flow leaving node i towards node j, c_{ij} are unit economic costs, b_j are the external inflows to node j, a_{ij} is the gain/loss rate on flow in arc ij, u_{ij} is the upper bound on arc ij, and l_{ij} is the lower bound on arc ij (Jenkins *et al.* 2001). The basic idea is to assign an economic cost to water scarcity for each agricultural or urban demand node in a region. Each demand node has a water delivery target and piece-wise linear costs for deliveries less than the target accumulate in the total system cost. The program described by equations (4.) through (4.4) is for a single time step, which in CALVIN is a month. To run time series of historical hydrology a sub-index k is added (see Draper *et al.* 2003).

Cost term c_{ij} in equation (4.) above is one of the most critical parameters in the program. The economic costs of water flowing from node i to node j in time step k can be as simple as operating costs or as elaborated as scarcity costs. Operation costs include pumping costs, and water treatment costs, per unit of water flow. Operation costs are mainly from urban water utilities reports.

Water scarcity is defined as the difference between the volume of water at which a users' willingness to pay for additional water equals water's marginal price, and the volume of water that is actually delivered (from Q* to Q' in Figure 4-2). Thus, scarcity occurs whenever the user's target demand Q* is not fulfilled. Water scarcity costs as depicted in Figure 4-2 can be seen as a change in consumer surplus. Scarcity cost is estimated from the integral between target and delivery water amounts below a water value (demand) curve, following techniques described in Gibbons (1986) and Young (Young 2005).

For this research, a representation of the hydrological system in the Colorado River Delta was built using CALVIN. As mentioned in Chapter 1 of this dissertation, the Colorado River Delta is a small region located in the northern international border of Baja California and Sonora (Figure 1-2). Region 6 of CALVIN is depicted in Figure 4-4.

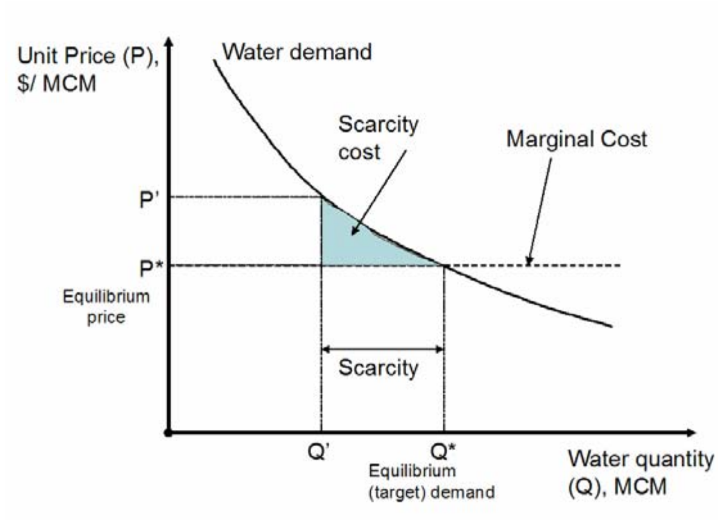

Figure 4-2 Scarcity and Scarcity Cost in CALVIN.

Agricultural land in the Mexicali Valley shown as the dark area in Figure 4-4, forms a rough triangle that goes from west of City of Mexicali to the east bank of the Colorado River and the Bypass Extension (Figure 4-3). The cities of Mexicali and San Luis Rio Colorado are the main two urban centers in the CRD (see Chapter 3). More than 3000 km in conveyance infrastructure distributes water to urban and agricultural users.

Water Commission 1992-1998).

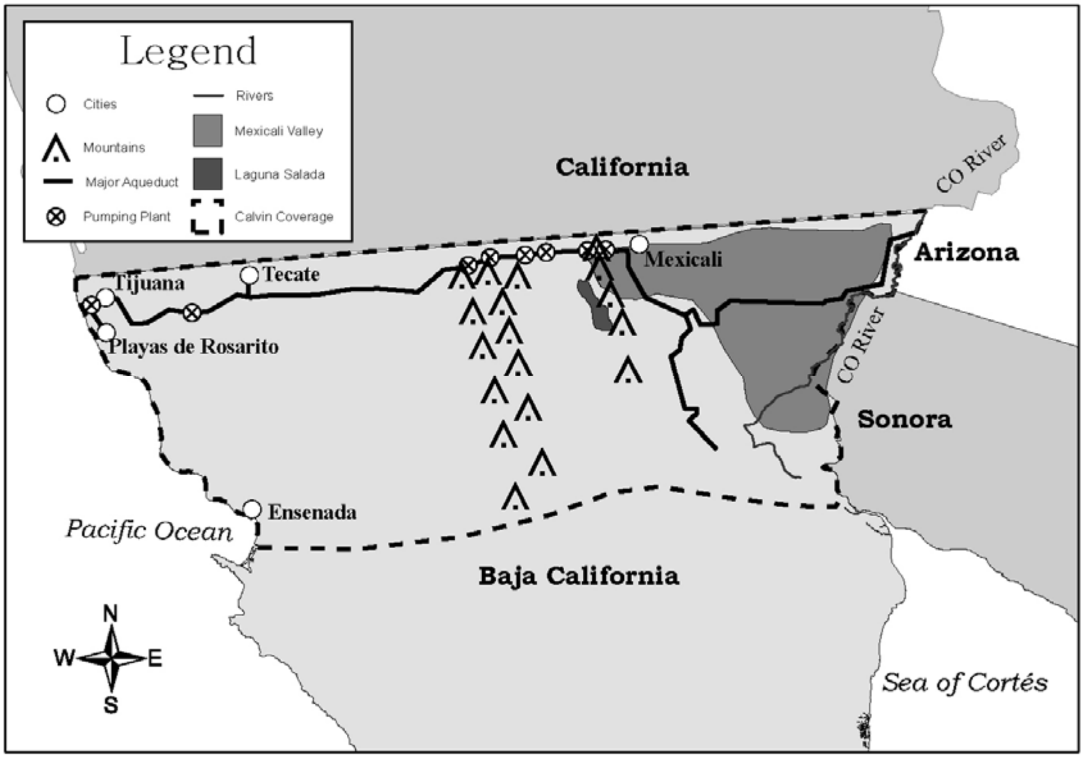

Figure 4-4 CALVIN Region 6, Northern Baja California (after Malinowski 2004).

4.4 A Representation of the Colorado River Delta in CALVIN

CALVIN model coverage for Baja California is depicted in Figure 4-4. Urban demands include the cities of Ensenada, Mexicali, Rosarito, San Luis Rio Colorado (Sonora), Tecate and Tijuana. Agricultural water uses include the valleys of Guadalupe, Maneadero and Mexicali. Hydraulic infrastructure in the model includes major canals and aqueducts, pumping stations, reservoirs and aquifers. For the Mexicali Valley, the focus of this study, hydrologic data includes time series of inflows from the Colorado River crossing the Mexico-U.S. border, and estimates of aquifer recharge for the Mesa Arenosa de San Luis Rio Colorado and the Mexicali aquifers. Base historic hydrology for this study includes 1999-2005 actual deliveries of water deliveries from the US to Mexico.

Figure 4-5 below shows a schematic representation of the Colorado River Delta in CALVIN. Appendix 4 of this dissertation depicts a one-page schematic for all northern Baja California (Region 6 in CALVIN), which is also available at the URL http://cee.engr.ucdavis.edu/faculty/lund/Default.htm. A region in CALVIN is made of nodes connected by links. Nodes can be demand nodes, pumping plants, hydropower plants (absent in Region 6), reservoirs, aquifers, ecological demand sites, sinks (*e.g.* Gulf of California), and lakes. Links include canals, aqueducts or rivers. Solid yellow circles are junction nodes, whereas cross marked yellow-circles are pumping stations. Orange ovals represent urban demand nodes, in this case the cities of Mexicali and San Luis Rio Colorado. Urban demands are divided into residential and non-residential (industrial). Light-gray ovals are agricultural regions, CALVIN requires different diversions for surface and groundwater return flows. Thus the four agricultural sub-regions in the CRD would require eight demand nodes (darker ovals). The upwardly pointing triangles are reservoirs (*e.g.* Morelos diversion Dam), whereas upside-down triangles are aquifers (such as the Mexicali aquifer).

4.4.1 Environmental Water Flows in the Colorado River Delta

The Sea of Cortes is in the bottom part of the schematic in Figure 4-5 and in the lower right corner of Figure 4-4 below. Environmental minimum water flows occur at Rio Hardy, the east upper fork of the Colorado River and ultimately the Sea of Cortes. As mentioned in Chapter 1 of this dissertation, current recommended minimum flows for the riparian corridor of the CRD are 40 MCM/year (Glenn *et al.* 2001) with pulse flows every four years of 320 MCM.

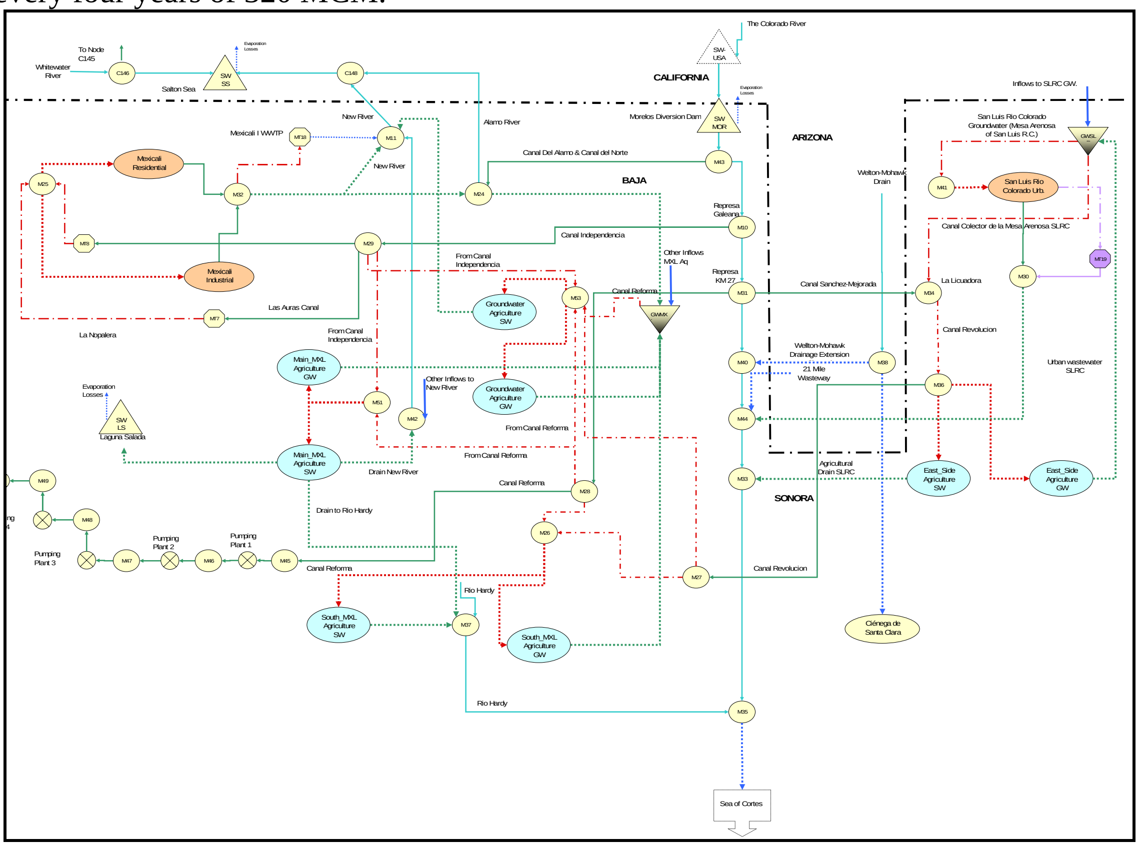

Figure 4-5 Fragment of CALVIN schematic representation of the Colorado River Delta.

The *Ciénega de Santa Clara* wetland (the yellow oval in Figure 4-5) is mostly fed from the Wellton-Mohawk Bypass Canal (MODE) at a rate of nearly 145 MCM/year. This drainage does not count towards Mexico's water allocation from the 1944 Treaty. Water in the MODE canal is mainly salty agricultural drainage from the Arizona Central Project north of Yuma, AZ. This system is somehow hydraulically independent of the riparian corridor north of Yuma, Arizona. The Cienega de Santa Clara wetland was brought to the attention of the scientific community in 1992, when Glenn (1992) highlighted the threat of starting operation of Yuma Desalting Plant in Yuma Arizona. This desalting plant would recover water from the Colorado River and dispose the resulting brine through the

MODE canal, reducing flows to the Cienega and increasing salinity up to 7200 ppm (Glenn *et al.* 1992). Due to high operating costs and strong political opposition this $240-million facility has never been employed.

4.5 Input Data for CALVIN in Baja California

Aside from a system schematic which identifies and connects geographic elements of a water management system, CALVIN requires several types of data: 1) hydrology, 2) operation costs, 3) scarcity costs 4) facilities and 5) institutional constraints. Figure 4-6 below shows how input data are used in CALVIN and how results follow post-processing. The network of Figure 4-5 is placed into a database built in CALVIN PRM NetBuilder, which stores node, link and pathname information in a Microsoft Access database. Metadata are included thus information on infrastructure and facilities can be improved as it becomes available.

Time series input data are mostly monthly series of inflows and evaporation rates for the time-span of the model runs. Paired data describe penalty functions (scarcity costs) for agricultural and urban water uses. Penalty functions correspond to term c in the objective function of equation (4.). Information on nodes and links from the database, along with time series and paired data are assembled into a linear program to be solved with HEC-PRM. The linear problem's code is written by the peripheral program called TestNetBuilder, and is a reproduction of the underlying optimization of equations (4.) to (4.4). Time series input data and paired data are stored in a format called DSS, which has been found to be efficient in terms of file size, compared to the more popular .MDB format of Microsoft Access. Results are monthly time series of storage, flow in links and shadow values on the constraints and storage capacity. Results are post-processed using Microsoft Excel macros and DSS interface tools.

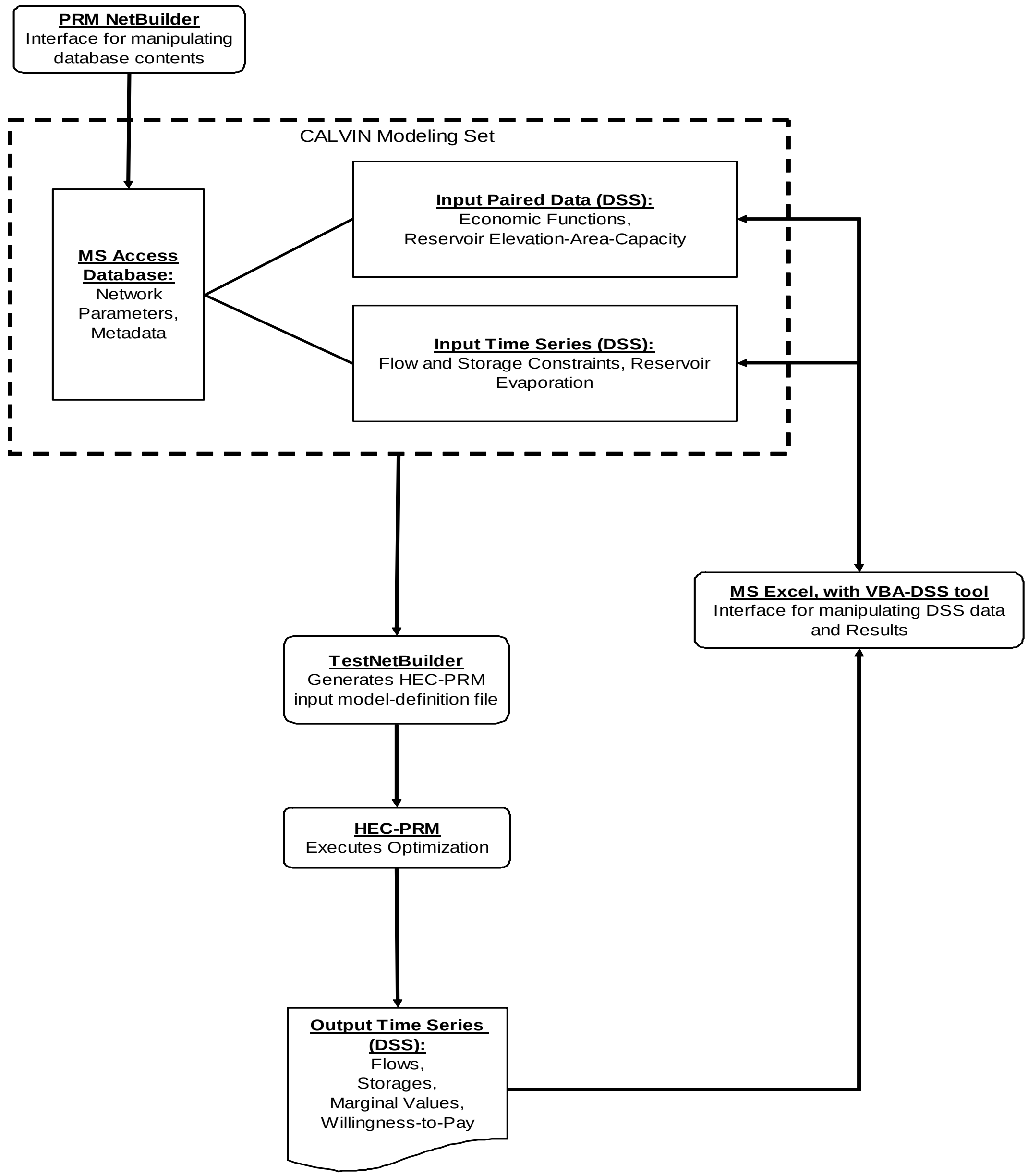

Figure 4-6 Input and output files and programs in CALVIN.

4.5.1 Hydrology

The CRD region has a relatively simple hydrology. The two main water sources are the Colorado River and two aquifers, the Mexicali and the *Mesa Arenosa* of SLRC aquifers. Colorado River deliveries from US to Mexico are meticulously measured at the two delivery points: The Morelos Dam and the Southerly International Boundary near San Luis Rio Colorado (Figure 1-2). As stipulated in the 1944 Water Treaty, the US must deliver at least 1,850.234 MCM/yr to Mexico. Records from the International Boundary and Water Commission (IBWC) exist for deliveries back from 1944 and before. For this study, actual deliveries from 1999 to 2005 are used as input time series. The aquifer has a relatively well know pattern of recharge and extraction. The National Water Commission (CNA), estimates annual recharge of the Mexicali aquifer in 700 MCM. Recharge comes mostly from agricultural runoff to the aquifer. From those 700 MCM, about 150 MCM/yr go from the US through the north-south limitrophe line (dashed line in Figure 4-7) between Arizona and Baja California (80 MCM), and the All American Canal (70 MCM), according to a hydrologic study from the former Secretariat of Water Resources (Secretaría de Recursos Hidráulicos 1972). About 50 MCM/year of lateral flow per year goes from the Mesa Arenosa of SLRC to the Mexicali Aquifer.

4.5.2 Facilities Operation and Scarcity Costs

Costs of pumping and water treatment (urban uses) come from operation reports and water plans of the public utilities in Mexicali and San Luis Rio Colorado (see CESPM 2006, OOMAPAS 2006). According to the CESPM utility's officials and their reports (CESPM), net revenues from billing water to users do not generate profit but just cover total costs.

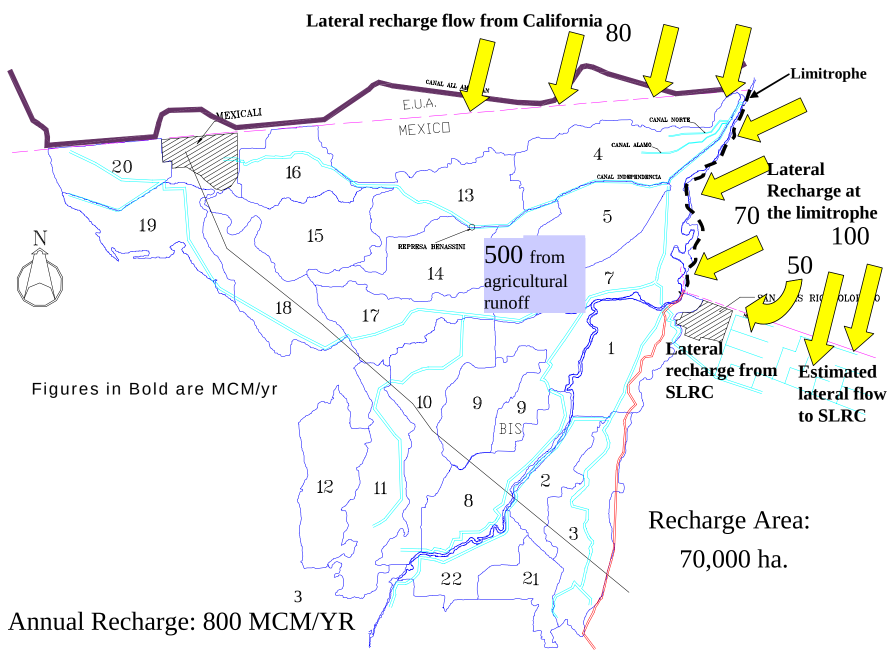

Figure 4-7 Recharge patterns for the Mexicali and San Luis Río Colorado Aquifers (adapted from Navarro-Urbina *et al.* 2002).

Scarcity costs can be agricultural or urban. For the agricultural scarcity costs (Chapter 2), CNA's irrigation district records were used. This data covers 60 months of water deliveries and cultivated land per crop for each irrigation sub-district or module (*módulo*). Production costs and factor usage other than land and water were obtained using statistical information from the Agriculture Ministry (SAGARPA). 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 agriculture, 3) East-side agriculture, and 4) West-side agriculture. Irrigation delivery demand curves for each irrigation area were found by systematically limiting water availability from 100% down to 60% of current use in ten percent steps. Numerical integration of the monthly water derived demand curves was used to obtain penalty functions Figure 4-2 following (Gibbons 1986). Overall, agriculture in the west of the Mexicali Valley has the lowest marginal value of irrigation water when availability drops below 80%. The main valley has the highest value, whereas the east side keeps a shadow value near the average of the four regions. The groundwater agriculture area has the steepest scarcity cost function, beginning as the lowest water value at full availability and exceeding the value in other two regions at the lowest level of availability.

Urban scarcity is calculated following the methods detailed in Chapter 3. Data sources for residential water use and pricing in Mexicali include CESPM and INEGI. Water consumption data from CESPM is monthly from January 2000 through December 2005. Consumption is disaggregated into 15 price blocks. For each consumption block, information includes total use, number of customers, and total revenue raised by the utility. Price at each block is a time series of 72 months (*i.e.*, block price rate changes monthly during the six-year time-span). Average household use is approximated by weighting per-customer use at each block rate by the number of customers per block. Income information comes from the National Income-Expenditures Surveys (ENIGH) for 2000, 2002 and 2004. Obtained price-elasticities are used to generate monthly penalty functions for water scarcity cost for Mexicali and SLRC, following Jenkins *et al.* (2001)and appendixes.

4.5.3 Conveyance Infrastructure and Facilities

Major conveyance infrastructure is included in the CALVIN representation of the CRD. Most of the information on facilities is a product of previous work (Malinowski 2004, Medellin-Azuara and Lund 2006). Included are the two main rivers in the CRD, namely the Colorado and the Hardy rivers; the transboundary Alamo River and the New River are also part of the representation in CALVIN. Morelos diversion is the starting point for receiving water in Mexico. Canals in the model include Alamo, Del Norte, Independencia, Reforma, Revolución and Sánchez-Mejorada. Two potable water and two wastewater treatment facilities are considered for Mexicali. One wastewater facility is included for San Luis Río Colorado.

4.6 Policy Alternatives and Modeling Sets

Consistent with the research objectives of this study, CALVIN is used to estimate the economic cost for agricultural and urban water users of various levels of CRD restoration flows. Water demand for off stream uses are projected for the year 2020. The marginal economic costs of environmental flows for the CRD are given by the Lagrange multiplier on minimum flows constraints for the CRD (*i.e.* equation 4.4 above).

Modeling sets of this study include year 2020 projected consumption in the urban centers and agriculture (Chapters 2 and 3 respectively). The Rio Colorado-Tijuana aqueduct, is assumed to have increased capacity to 5.2 m^3/s, and is operated at full capacity to supply growing urban demands in the Tijuana metropolitan area. Mexicali and San Luis Rio Colorado use becomes roughly 100 and 42 MCM/year, respectively. Minimum water flows for the CRD follow current recommendations of 40 MCM/yr minimum constant flow and pulse flows of 320 MCM every four years, an average flow of 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 by purchasing water from agricultural and urban users in the Mexicali Valley.

The second alternative adds treated wastewater at a cost of $200/TCM to the options available in the first alternative. Wastewater reuse is limited by treatment plant capacity (about 15.8 MCM/yr), with capacity cost being omitted from the model. Finally, the third alternative allows water to be purchased from other locations, presumably the US, at an inexpensive rate of 30 dollars per TCM, in addition to the options available in the first and second alternatives. While this price it is not representative of the contentious price agreement for water 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.

4.7 Model Results

Model runs for each policy alternative and level of minimum inflow requirements were performed by CALVIN. Results of interest include the overall cost to the Mexicali Valley region, quantities of water scarcity for urban and agricultural uses, the marginal cost to agricultural and urban users of environmental outflows (shadow values or Lagrange multipliers 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 in the CALVIN representation of the system. For this set of modeling runs, outflows to the Colorado River Delta were set at 10 MCM per month. Water scarcity, scarcity cost, and shadow values of environmental flows and transboundary flows were analyzed.

Table 4-1below, 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, San Luis Rio Colorado, 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 4-1).

Interestingly, willingness to pay for additional water from the US is only $13.5 dollars/TCM. For water year 2004-2005, the water price to farmers was about $7 dollars/TCM. Scarcity is not uniform in the Mexicali Valley; agriculture in the west side of the valley is the most vulnerable to water shortages. East side and the main Mexicali Valley are not expected to experience scarcities due to population growth.

Scarcity and its cost grow in the hypothetical case that 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/yr. 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 shadow value of environmental flows is estimated to average $52.2 dollars per TCM. Willingness to pay for additional water from the US 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 if operating costs remain constant. 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 dollars per TCM. Willingness to pay for additional transboundary water imports remains low at $22.85/TCM in average. However, 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 water flows for the CRD, the net present value of the wastewater reuse facility's to the 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 more dramatically. Figure 4-9 shows a model run in the last column where water can be bought in any amount at a rate of $30/TCM. This is as if additional Colorado River water were available to Mexico at $30/TCM. 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.

Table 4-1 Annual water scarcity, scarcity costs, and opportunity costs for environmental flows to the CRD and US-Mexico transboundary Flows.

	Status Quo (without environmental flows)	**Mandated Minimum Average Flows of 10 MCM/month**		
		Water Markets	**Facilities & Markets**	**Facilities, Markets & US flows**
Annual Water Scarcity for Agriculture (MCM/yr)	66.2	158.4	144.3	121.2
Annual Scarcity Cost for Agriculture (K$/yr)	1,460	3,830	3,406	2,819
Shadow Value of Environmental Flows ($/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 US dollars.

The same three policy alternatives were analyzed over a wide range of minimum environmental flows. Figure 4-8 shows the results of gradually increasing mandated water flows for the CRD from zero to 20 MCM/month (zero to 240 MCM/year). 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 high cost of treated wastewater. For 2005, prices for wastewater range from $200 to $600/TCM (CESPM 2006), whereas agricultural water fee 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 trans-boundary water imports remains less than $40/TCM for all cases. Opportunity costs on environmental constraints flatten slightly after recommended monthly flows if low-cost water is available.

The total annual opportunity costs of delta environmental flows are depicted in Figure 4-9. As expected from Figure 4-8, inexpensive ($30/TCM) water imports become the most cost effective when minimum flow requirements exceed 180 MCM/year. This figure is much lower than the values of water in southern California estimated in other CALVIN studies (*e.g.* Pulido-Velazquez *et al.* 2004) which can be as high as $80/TCM or observed prices in recent long-term water markets in southern California (over $160/TCM). When water import prices are raised to $60 (not shown), opportunity costs in the Mexicali Valley of environmental flows were found to be close to $70 /TCM.

Given the relatively high economic value of urban water uses in the Mexicali Valley, water scarcity 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/yr 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.

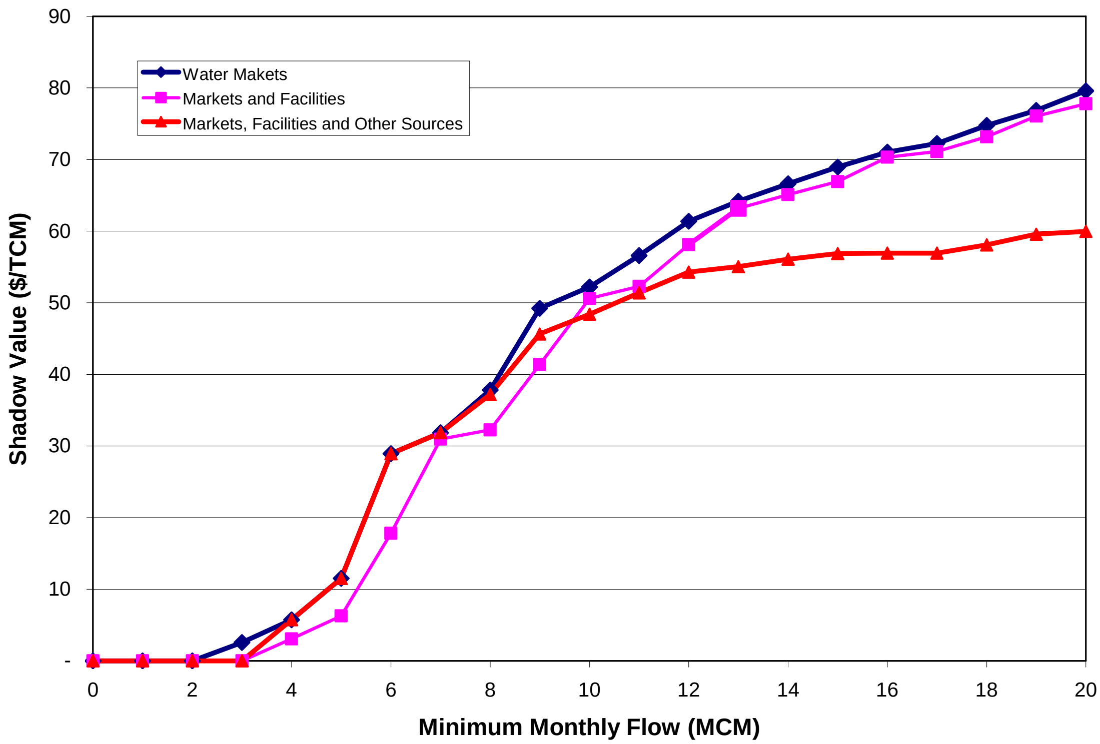

Figure 4-8 Shadow value of minimum environmental flows in the Colorado River Delta.

For minimum environmental flows to the delta from 0 to 20 MCM/month, scarcity is greater when no alternative sources are available. Willingness to pay for additional transboundary water flows from the US at Morelos Dam is quite low for the range of values in the model (Figure 4-10). These results resemble shadow value trends for the minimum flow constraint in the CRD (Figure 4-8).

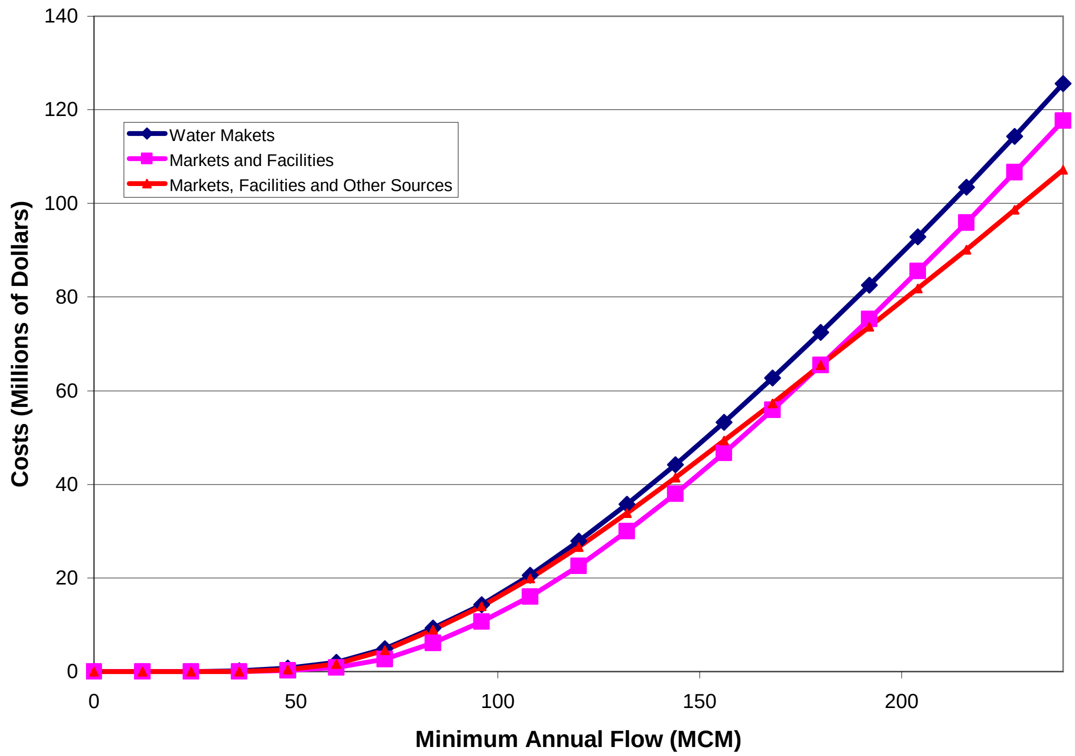

Figure 4-9 Total annual opportunity cost of minimum flows in the Colorado River Delta.

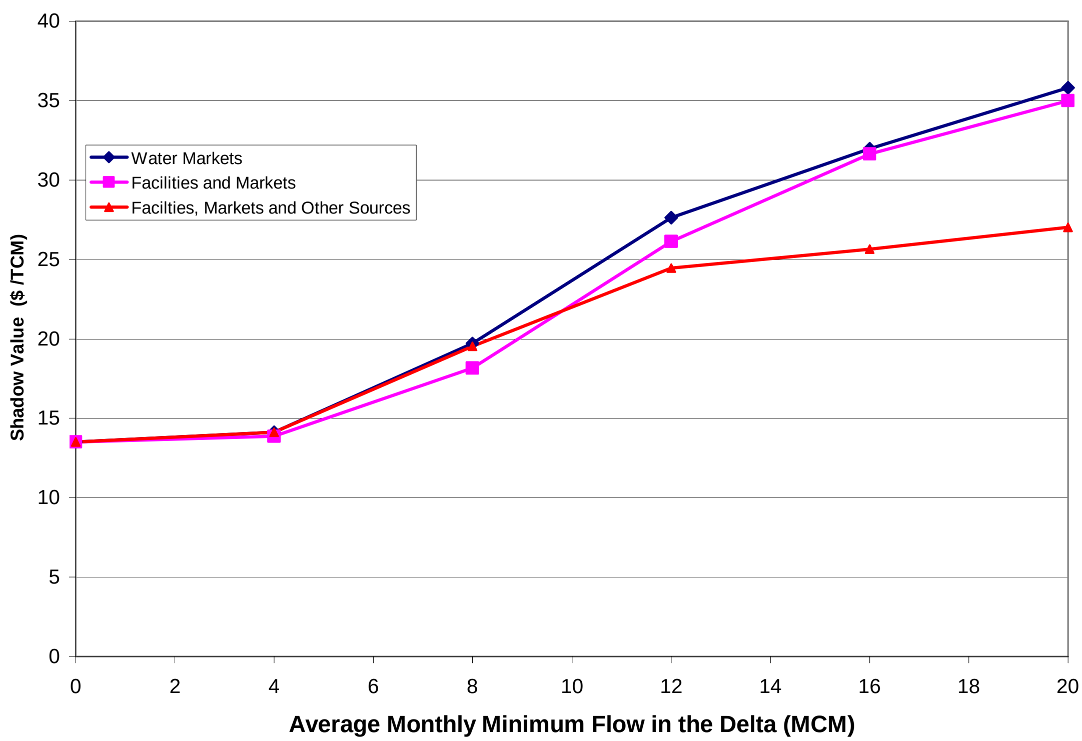

Figure 4-10 Willingness to pay for additional transboundary water flows from the US.

It is possible to use these model results as a framework to estimate the perceived economic value of environmental restoration flows for the Colorado River Delta, without the shortcomings of environmental benefits functions pointed by Shabman and Stephenson (2000). Previous applications of systems analysis for instream flow economic valuation such as Diaz *et al.* (1992) and Booker and Young (1994) follow a quite similar approach to the one presented in this study. Diaz et al (1992) however, maximize benefits of instream uses while restricting minimum instream flows. Booker and Young use a minimum shortage cost objective function to represent institutional priorities. However, when salinity damage is incorporated in their optimization program net-benefit functions accounting for salinity functions are used instead. According to Freeman (2003), “the symmetry of benefits and costs stems from the fact that ultimately all costs take the form of utility losses to individuals in their dual roles as receivers of income and consumers of market and non-market goods and services” (37). Instream uses in the CRD would mostly be for habitat conservation as no hydropower is generated. Thus, as in Diaz *et al.* (1992), instream uses are represented as minimum flow constraints with the implicit ability to provide shadow values. The 1944 Water Treaty and Minute 242 of the IWBC stipulate minimum water deliveries and allowable salinity levels through the Colorado River down to Mexico. Salinity damages had been a concern in the Mexicali Valley (see Brownell and Eaton 1975, Fuentes *et al.* In press). However, unlike Booker and Young (1994) the upper bound in Minute 242 lessens the role of potential salinity damage (as modeled by these authors) for agriculture and urban use located upstream of the CRD and the Hardy River.

Figure 4-8 and Figure 4-9 indicate the policy making 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 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.

4.8 Limitations and Sensitivity of the Model

Limitations arise both from the model itself and the study cases represented. Main limitations of CALVIN have been discussed in detail in Jenkins *et al.*(2001), and can be classified into three groups namely data, simplified representation of a system and perfect foresight.

Availability and quality of data are perhaps the most common challenge to many models, and so are for modeling water systems. Nevertheless, inasmuch northern Baja California is an extremely dry, smaller, and relatively simple region in CALVIN, hydrology and infrastructure are relatively simple as well. Establishing the Colorado River Delta hydrologic and hydraulic network, composed of the Colorado River and two aquifers, required less data than similarly sized regions in California. There is no water storage other than the aquifer and the hydraulic network, and no hydropower. Records on water deliveries from the US exist even before the 1944 Water Treaty. Rainfall records are available, although rainfall is not a significant source of water for the study area. On the other side, information on instream water use values such as fishing and recreation has not been estimated in this author's knowledge.

The linear formulation of the optimization program also imposes some restrictions. Interactions between surface and groundwater may well be a linear function. These representations could not be incorporated without making non-network flow constraints. The same would apply for other relationships (*e.g.* water flows and water quality) in a water system. Groundwater and surface water interaction is mostly represented as a fixed time-series of inflows into the Mexicali aquifer, that is reasonably understood nowadays (see Navarro-Urbina *et al.* 2002).

One limitation inherent in a model like CALVIN is the implicit assumption of perfect foresight. As a deterministic optimization model, the program knows the hydrology for the entire modeling period in advance. Thus, water is allocated to minimize total cost during the modeling period taking into account that there are some *dry* and some *wet* years. Draper (2001) addresses in detail implications of having perfect foresight and proposes to divide the entire time-period model into sequential and shorter pieces connected by a carryover storage value function. While this offers advantages in modeling reservoir operations, this would imply less gain in as the Colorado River Delta, characterized by the absence of reservoirs and a relatively stable hydrology determined to a great extent by the binational water treaty supported by very large storage projects in the US. Therefore, the role of the intertemporal flexibility in operations provided by local storage capacity is lessened in the CRD.

Demand projections in this study rely in some underlying assumptions. First, demands are static. The underlying assumption is that urban and agricultural demand patterns will not change regardless of the year type (dry or wet). Another challenge to the approach of this study is a potential underestimation of urban and agricultural water conservation practices. Additional conservation practices may reduce scarcity and scarcity costs for agriculture even if the CRD has been endowed with minimum water flows. Finally, agriculture is estimated to remain at current (2000-2005) levels. For this case study and given the lower bound on water availability for the CRD, having dry and/or wet year formulations may improve the application marginally at a high computational cost. Public utilities may implement improved commercial and conveyance efficiency by year 2020. Furthermore, consumers may be willing to adopt water conservation practices. Finally, water quality considerations are currently out of the scope of CALVIN[4]. Increased salinity in water perhaps as a result of low water flows may increase water treatment costs and decrease agricultural yields.

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[4] For an application of an optimization model considering salinity in the Colorado River see Booker and Young (1994) and Lee *et al.* (1993)

With these limitations, application of CALVIN is that of a screening model, aimed to identify promising water management strategies. Representation of a water system with CALVIN is not static and may improve as knowledge of the aforesaid water system improves.

4.9 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 value increases to about $80/TCM when recommended flows are roughly doubled.

2. Wastewater reuse facilities have only a small supporting rule 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. 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.

4. This 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 tradeoff curves developed from this kind of study could support decision-making and economic valuation of environmental flows by decision makers.

This work also offers methodological contributions to the field of valuing environmental uses of water. Unlike traditional valuation techniques for this type of use, water value comes from opportunity cost to other uses. Valuation methods such as contingent valuation, travel cost and heuristic methods are aimed to obtain economic demand curves for environmental uses from consumers. One advantage of the approach proposed by this study is that water for production activities is implicit in the valuation. On the other hand, economic welfare measures such as change in consumer surplus from different environmental water flow levels could not be evaluated, 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.

Chapter 5 Conclusions

Systems analysis with hydro-economic models offers a framework to integrate hydrology, competing water demands, and hydraulic infrastructure, as well as institutional policies and physical constraints in a region. Environmental water uses are often included in hydro-economic models as minimum flow restrictions. Optimization models that incorporate environmental water uses in this fashion provide shadow values of these instream uses. The CALVIN model is a systems analysis tool that prescribes promising water management alternatives for optimized scenarios. With the CALVIN model minimum environmental flow restrictions can be incorporated and explored within a regional hydro-economic network. Shadow values of the environmental flows represent opportunity costs for competing water uses including agricultural and urban.

Environmental water shadow values at different minimum flow levels provide information to evaluate water management alternatives including best sources of water for restoration. Shadow values under this method depart from other non-market valuation methods such contingent valuation and travel costs that remain controversial in their development and results.

The lower Colorado River Delta offers an excellent case study to apply systems analysis for habitat conservation and restoration. Extremely-arid weather, fast-growing border cities and prominent agriculture characterize this region of Mexico.

Contributions of this study are both methodological and study-site related. Methodological, contributions on water valuation are not limited to valuate environmental uses. A consistent integration of agricultural, urban and environmental water uses into a single regional model was developed.

In addition to methodological advantages over empirical valuation techniques, the agricultural water demand model for the Mexicali Valley using positive mathematical programming (PMP) offers innovations and improvements over previous studies with PMP and others in the linear programming literature. A flexible production functional form and a detailed dataset of monthly water deliveries per crop at a sub-district level characterize PMP application of this dissertation. Results from the model confirm previous expectations on shadow values of agricultural water in the Mexicali Valley. Irrigation water has the highest marginal value for groundwater agriculture and for sub-districts in the main valley where land quality increases production yields. Furthermore, the shadow values of agricultural water seem to exceed current average irrigation fees of $10/TCM, suggesting that water in agriculture is underpriced. Finally, water price-elasticity for agriculture in the main Mexicali Valley was found to be elastic. Water demand was price-inelastic for the rest of the agriculture, which accounts for two thirds of all agricultural water use. Therefore policies to improve water use efficiency in agriculture through water pricing may result in small changes in agricultural water use overall.

The urban water demand model also offers some innovations and advantages for literature on residential water demand using aggregated consumption data. A two-stage regression approach resolved the endogeneity issues associated with marginal price under increasing block rate structures. One of the most salient contributions of this water demand model was the ability to contrast water price-elasticity between two rate structures: increasing and a constant block rate schedule. As expected, water demand is more sensible to price adjustments for increasing block rate structures. Urban water utilities can find implementing increasing block rate pricing structures worthwhile, to reduce need for additional infrastructural projects.

Finally, the regional systems analysis approach employed in this study allows the policy analyst to elicit promising water resource management strategies taking into account competing water uses. A quantitative representation of a water resources system offers the possibility of evaluating different scenarios for a particular policy issue. As more information on the region becomes available, it will be possible to integrate this information into the model to improve understanding of a system and evaluate water management alternatives.

Several worthwhile policy alternatives for restoring and maintaining ecosystem functions in the CRD. Among these policies, mandated flow regimes for the CRD and liberalized markets for water in the Mexicali Valley appear to offer the most cost effective alternatives for addressing water quantity issues in the CRD. Additional infrastructure for water treatment, conveyance and reuse only provide small gains. Other findings from this model support the idea that shadow values of environmental flows can be so small that interboundary water transfers from the US will not make international water banking cost-effective for restoration.

For Baja California in general, water supply problems in the next few decades may be ameliorated with the development of water markets. Despite growing water needs in the border cities, water can be acquired from competing uses within Irrigation District 014 considering the forthcoming Rio Colorado-Tijuana’s aqueduct capacity expansion.

Future research for applying this systems analysis approach to the CRD includes an interconnection of the Baja California model with the larger CALVIN model in U.S. California. While water transfers from US to Mexico are not a cost effective water source for the CRD, coordinated operation between southern California and north Baja California in CALVIN offers the possibility of better evaluation of infrastructure expansion projects. Improvement of economic representation of water uses in cities and smaller agricultural regions also can be incorporated as they become available.

Systems analysis for environmental water use is a cumbersome task which demands knowledge of a hydraulic network, competing beneficial uses and institutional constraints. Nevertheless, this is a case in which the game clearly is worth the candle. Systems analysis not only provides a setting to incorporate hydraulic and infrastructural network information, but also an integrated quantitative understanding of the network’s supplies and its water demands. Results of this study highlight the importance of working out institutional constraints and suggest ways to take water management alternatives from the modeling laboratory into the real world. Systems analysis and the CALVIN model in particular are valuable screening tools that can provide policymakers quickly and effectively with information on policy alternatives. They provide a framework for integrating knowledge about water management in regions, however large or small they may be, in which competing uses and tradeoffs are complex.

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Appendix 1 Converting SWAP Shadow Values into CALVIN Penalty Functions

From Chapra and Canale (1988), a total value function using the trapezoidal rule is defined by the following formula:

$$I = \frac{h}{2}\sum_{n}\left[f(x_{n-1}) + f(x_n)\right] \qquad \text{(A.1.1)}$$

$$h = (b - a)/N \qquad \text{(A.1.2)}$$

I is the total value function, x is the independent variable, and f is any function of x, and h. For this case, f(x) will represent a shadow value whereas x will be an inflow. Where N is the maximum number of inflows minus one, b is the largest inflow value and a is the smallest inflow value. The net inflows are the product of the applied water and the ratio of farm irrigation efficiency and basin irrigation efficiency; formally,

$$Inflows = AW\frac{FE}{BE} \qquad \text{(A.1.3)}$$

Based on historical data from Irrigation District 014, basin efficiency in the Mexicali Valley is assumed to be 90% (Sánchez-Munguía 2004). Seasonal application efficiency (SAE) is given by the following formula.

$$SAE = (ETAW + LR)/AW \qquad \text{(A.1.4)}$$

Where ETAW refers to evapotranspiration minus the effective rainfall and LR is the leaching requirement. Return flows are divided in CALVIN into surface returns and groundwater returns. Two separate sets of penalty functions are then required for each return type.

Appendix 2 Derivation of CES parameters for PMP

Derivations of the constant elasticity of substitution production function follow (Howitt 1995). From the CES functional form in equation 2.1 above with constant returns to scale: ν=1, and sum of betas equal 1:

$$Y_{gi} = \tau_{gi}\left[\sum_j \beta_{gij} X_{gij}^{-\rho}\right]^{-1/\rho} \qquad \text{(A.2.1)}$$

Where, ρ=(1-σ)/σ. Using the first order conditions of a profit maximization problem where sub indexes g and i have been dropped for simplicity:

$$\frac{\partial y}{\partial x_i} = \rho\beta_i x_i^{(1-\rho)} \frac{1}{\rho}\tau\left(\sum_j x_j^{-\rho}\right)^{-1-1/\rho} \qquad \text{(A.2.2)}$$

$$\beta_1 = 1-\beta_2-\beta_3-\beta_4 \quad \frac{\partial y}{\partial x_i} = \beta_i x_i^{(-1/\sigma)}\tau\left(\sum_j x_j^{-\rho}\right)^{1/(\sigma-1)} \qquad \text{(A.2.3)}$$

$$\frac{\omega_j}{\omega_l} = \frac{\beta_j x_j^{-1/\sigma}}{\beta_l x_l^{-1/\sigma}} \quad \text{where } j,l = 1,2\ldots,J \qquad \text{(A.2.4)}$$

Recalling, constant returns to scale implies that sum of all β_j is one. Thus for the case of four inputs (*i.e.* J=4).

$$\beta_1 = 1-\beta_2-\beta_3-\beta_4 \qquad \text{(A.2.5)}$$

And having everything as a function of β_1 yields:

$$\beta_1 = 1-\beta_1\left(\frac{\omega_2}{\omega_1}\frac{x_1^{-1/\sigma}}{x_2^{-1/\sigma}} + \frac{\omega_3}{\omega_1}\frac{x_1^{-1/\sigma}}{x_3^{-1/\sigma}} + \frac{\omega_4}{\omega_1}\frac{x_1^{-1/\sigma}}{x_4^{-1/\sigma}}\right) \qquad \text{(A.2.6)}$$

$$\beta_1 = \frac{1}{1+\left(\frac{\omega_2}{\omega_1}\frac{x_1^{-1/\sigma}}{x_2^{-1/\sigma}} + \frac{\omega_3}{\omega_1}\frac{x_1^{-1/\sigma}}{x_3^{-1/\sigma}} + \frac{\omega_4}{\omega_1}\frac{x_1^{-1/\sigma}}{x_4^{-1/\sigma}}\right)} \qquad \text{(A.2.7)}$$

$$\beta_1 = \frac{1}{1+\left(\frac{x_1^{-1/\sigma}}{\omega_1}\sum_{j\neq 1}\frac{x_j^{-1/\sigma}}{\omega_j}\right)} \qquad \text{(A.2.8)}$$

Formulation for all $\beta_l(\beta_1)$, where $l \neq 1$

$$\beta_l = \frac{1}{1+\left(\frac{x_1^{-1/\sigma}}{\omega_1}\sum_{j\neq 1}\frac{x_j^{-1/\sigma}}{\omega_j}\right)}\frac{\omega_l}{\omega_1}\frac{x_1^{-1/\sigma}}{x_l^{-1/\sigma}} \qquad \text{(A.2.9)}$$

Parameter τ in the production function, is given by:

$$\tau = \frac{yld \cdot \tilde{x}_{land}}{\left[\sum_j \beta_{gij} X_{gij}^{-\rho}\right]^{-1/\rho}} \qquad \text{(A.2.10)}$$

Finally, the parameters α and γ for the PMP cost function are:

$$\alpha_j = \omega_j \quad \text{and} \quad \gamma_j = \frac{\lambda_2}{2\tilde{x}_{land}} \equiv \frac{v_{gi}\, yld_{gi}}{\eta_{gi}\tilde{x}_{gij}} \qquad \text{(A.2.11)}$$

Appendix 3 Valuation of Water for Urban Uses

Modeling in CALVIN requires valuation of scarcity costs for demand locations. These scarcity costs are represented by piecewise-linear penalty functions Jenkins *et al.* (2003). Penalty functions are obtained from numerical integration of water demand curves of the demand locations.

Young (2005) presents a procedure for deriving an at-source value for residential water (and in this case, penalty functions), as the integral of a price-quantity observation in an estimated demand curve. In previous studies, Young and Gray (1972) adapted this procedure from James and Lee (1970), who integrated a constant elasticity demand function to obtain the value of water. This technique is pervasive in water valuation literature (*e.g.* Gibbons 1986).

From the traditional definition of price elasticity:

$$\eta = \frac{dQ}{dP} * \frac{P}{Q} \qquad \text{(A.3.1)}$$

Where η is the price-elasticity of demand, P_o and Q_o are observed price and quantity respectively. A demand functional form in which elasticity remains constant is assumed. The inverse price demand P(Q), can be obtained by integration of the equation above analytically following James and Lee (1970):

$$\int \frac{dP}{P} = \frac{1}{\eta} \int \frac{dQ}{Q} \qquad \text{(A.3.2)}$$

which yields

$$\ln P = -\frac{1}{\eta} \ln Q + C_1 \qquad \text{(A.3.3)}$$

taking exponentials gives:

$P = Q^{-1/\eta} C_2$ (the inverse demand function), where $C_2 = \frac{Q_o^{1/\eta}}{P_o}$

And the area below the curve if demand in the nearby of Q_o changes from Q_1 to Q_2:

$$Area = \frac{P_o Q_o^{1/\eta}}{1 - 1/\eta} * \left(\frac{Q_2}{Q_2^{1/\eta}} - \frac{Q_1}{Q_1^{1/\eta}} \right) \qquad \text{(A.3.4)}$$

These area represents the valuation by the consumers willingness to pay for additional $\Delta Q = Q_2 - Q_1$ units of water. Griffin (1990) found that valuation is sensitive to the functional form chosen and expressed preference for a translog form.

Monthly penalty functions for a projected year (2020) are adapted by making area equation above equal to penalty for each time step. Thus, the constant of integration C_2
Is obtained from a base year (2005) as:

$$C_{2,m} = \frac{P_{2005,m} Q_{2005,m}^{1/\eta}}{1 - 1/\eta_{2005,t}} \qquad \text{(A.3.5)}$$

where m is the month of the base year. The penalty becomes then a function of the delivered amount of water for month m (a decision variable in CALVIN), versus the projected (target) water amount for that month, $\overline{\overline{Q}}_m$, formally,

$$Penalty_m(Q_m) = C_{2,m} Exp\left\{\overline{\overline{Q}}_m^{\,1+1/\eta} - Q_m^{1+1/\eta}\right\} \qquad \text{(A.3.6)}$$

Appendix 4 CALVIN Region 6: Baja California and San Luis Rio Colorado, Mexico