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Abstract

The research discussed in this paper is concerned with the twin cities of Nogales, Sonora-Nogales, Arizona and the Santa Cruz River. The headwaters for the Santa Cruz River are in southeastern Arizona where the river flows south, crossing the U.S.-Mexico border into the state of Sonora. The river eventually turns north in Sonora and flows back to the U.S.-Mexico border, crossing back into Arizona near this set of Twin cities. The management of this river and its related resources are the focus of this paper.

This paper is organized as follows. First, the following section provides a discussion of the geographic location of the Santa Cruz River. This section also includes a discussion of the specific water resource management issues that are of particular concern in the study region. A "stylized" water resource management model is presented in the Section 3. Section 4 will focus on the marginal decision rules that correspond with the maximization of net benefits of water resources management for the Santa Cruz River Basin as a hydrologic unit. We will discuss a range of water pricing and allocation rules that will fit within the existing institutional structure for water resource management.

Keywords: water resource management; transboundary water problems; water pricing options
JEL Codes: Q25, Q28

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Introduction

The Nogales-Nogales area which is located in the Colorado River basin is a community with growing populations and increasing pressure on water; additionally there is little water storage capacity in this region. Sonora's Nogales population increased 50 percent in the 1990s and is now more than 212 thousand people; between 2000 and 2020 its population is expected to increase by 86 percent. Nogales, Arizona has a population of less than 30 thousand, but during the 2000-2020 period it is expected to grow by 67 percent. Water in this region comes mainly from the Santa Cruz and San Pedro Rivers that flow between the U.S. and Mexico, and from the Colorado River that flows form the U.S. to Mexico. All three rivers have treatment plants, some only partial operational, but that does not seem to be enough since these rivers are highly polluted, threating groundwater in the region. This may be due to the maquiladoras, services, and agribusinesses that are the main source of economic activity and they help build pressure across the border for scarce water. Water tables for aquifers in the region are mostly in a state of decline, leaving residents, particularly in the Sonoran (Mexico) side, vulnerable to water shortages, especially during drought years (Ingram and White 1993, Frisvold and Caswell, 2000).

The management of water resources along the border is made difficulty by the existing institutional complexities. The International Boundary and Water Commission (IBWC for the U.S./CILA for Mexico) was established as a result of the 1944 U.S.-Mexico Water Treaty on Utilization of Waters of the Colorado and Tijuana and of the Rio Grande to manage surface water. This treaty established water rights on these main rivers; however, water from other smaller rivers is unilaterally taken by each country. The 1944 treaty addresses water quantity issues from the main rivers only. Initially it did not discuss water quality and due to this, controversies keep surfacing. For example, the recent conflict over the All-America Canal is due to diversion of surface water from the Colorado River to farmers in the Imperial Valley and from the reduction in groundwater recharge due to the lining of canals in the U.S. This reduces aquifer recharge and increases salinity in the Mesa San Luis aquifer that supplies water to Mexican farmers in Mexicali (Frisvold and Caswell 2000). Even though water allocation is mentioned in the 1944 treaty, water quality is not addressed, and water with higher content of dissolved solids and higher salinity is being delivered to Mexico. This in turn lead to the 1973 amendment that limits total dissolved solids (TDS) in the water flowing towards Mexico, and stated that they have to be within 115 ppm of TDS in the Imperial Dam in the U.S. This addresses relative salinity, but not absolute salinity issues that will ultimately affect both countries.

Managing surface water has been fraught with challenges, but these challenges have been much smaller than those arising from allocating groundwater resources, given the lack of consensus around groundwater use. Groundwater has been exploited as a common property resource leading to reduced water quality and increased salinity. In 1973 an addendum to the 1944 Treaty, Minute 242, limited groundwater withdrawals on both sides along the border to control salinity, and each nation agreed to consult the other, prior to any future groundwater developments. This amendment has not been observed in part because of its lack of clarity. Some think that local agreements rather than bilateral agreements will probably develop across stakeholders in the border area (Mumme 2004). At this time no other agreements have been put in place.

One issue that complicates things further when developing schemes for better water management is the level of government at which water use is regulated. While Mexico does things through the National Commission of Water (CAN) at the federal level, the U.S. handles it at the state level. In addition, each state in the U.S. has different rules regarding ownership, exploitation and use.

A range of studies can be found in the literature that attempt to identify the key contributors to the water resource problems along the border and also propose model structures that can be used to develop policy solutions. The common model strategy is a game-theoretic structure as reported in Fernandez, (2004, 2013), Frisvold and Caswell (2000, 2008), and Nakao et al. (2002). Chermak et al. (2005) develop a continuous time dynamic joint maximization model that features an aquifer as a transboundary resource. Most of this research gives little consideration to identifying a workable and a broadly holistic solution to the transboundary water resource management problem.

The studies cited, although limited in numbers, are indicative of the existing research that has been done on transboundary water resource management problems. Most of the studies use a joint maximization approach in their problem formulation, which can also be thought to be a cooperative game theory formulation. There are other arrays of game theory formulations that have been the basis of this research. A number of studies such as those by Lekakis (1998) and Giannias and Lekakis (1996, 1997) pose the transboundary water resource management problem as a form of bilateral negotiation (many of these are represented as bilateral monopoly models). We conclude that these studies tell us what types of outcomes should be considered, but they have little to say about the concrete institutional design and computational system for actually approaching a workable solution for policy purposes. This becomes increasingly important as we see more serious climate change outcomes in a region that is characterized as arid.

The research discussed in this paper is concerned with the twin cities of Nogales, Sonora-Nogales, Arizona and the Santa Cruz River. The headwaters for the Santa Cruz River are in southeastern Arizona where the river flows south, crossing the U.S.-Mexico border into the state of Sonora. The river eventually turns north in Sonora and flows back to the U.S.-Mexico border, crossing back into Arizona near this set of Twin cities. The management of this river and its related resources are the focus of this paper.

This paper is organized as follows. First, the following section provides a discussion of the geographic location of the Santa Cruz River. This section also includes a discussion of the specific water resource management issues that are of particular concern in the study region. A "stylized" water resource management model is presented in the Section 3. Section 4 will focus on the marginal decision rules that correspond with the maximization of net benefits of water resources management for the Santa Cruz River Basin as a hydrologic unit. We will discuss a range of water pricing and allocation rules that will fit within the existing institutional structure for water resource management.

2. The Nogales, Sonora-Nogales, Arizona Santa Cruz River Border Region

The study region for this research begins in the upper reaches of the Santa Cruz River Basin in the Mexican state of Sonora near Miguel Hidalgo, continuing along the Santa Cruz River as it flows back into Arizona. The Arizona portion of this study region is limited to Santa Cruz County because some of the more interesting management issues are located in this general area.

The historical streamflow records for the portion of the Santa Cruz River Basin included in our study region indicate that little or no streamflow is available for reliable water supply over the course of a typical year. The major aquifer is the Santa Cruz Aquifer which is described as a shallow aquifer that is interconnected with the Santa Cruz River and follows the Santa Cruz River over its normal course of flow. This aquifer has been a major source of water supply for Nogales, Sonora, but seems to be an unreliable source during certain periods of the calendar year. The groundwater wells for Nogales, Sonora are located southeast of the city while the wells for Nogales, Sonora are generally northeast of the city. These wells pump water from the Santa Cruz Aquifer.

The demands and/or uses of water in our study region are also important. The main municipal water demands in Santa Cruz County will be Tubac, Tumacacori, Rio Rico, and Nogales, Arizona. Irrigation demands for agricultural use are also important in Santa Cruz County. The major agricultural activity is ranching with hay crops for livestock being an important activity.

Another important issue is the management of treated wastewater. Sewage from the Nogales Sonora—Nogales, Arizona area is transported to the Nogales International Wastewater Treatment Plant (NIWTP) which located near Rio Rico. The effluent discharge from the NIWTP has the potential to be an important source of water supply in the Santa Cruz River watershed upstream from Rio Rico where the effluent enters the Santa Cruz River. But there are some significant issues with this. As noted previously, the NIWTP has a capacity of 17.2 MGD. Minute 276 has allocated 9.9 MGD of this capacity to Mexico. On average, 15.4 MGD is processed by the NIWTP, but 12.5 MGD of influent comes from Mexico. Minute 276 also gives Mexico the right to recapture its effluent from the NITWP or keep its effluent from the NITWP from entering the U.S. This means that 80 percent of the effluent cannot be counted on as a long-term supply of water in Arizona due to Minute 276. In the short run, the capital energy costs to physically deliver such a large amount of treated water back to Mexico, given the steep gradient for pumping the water up hill, are considered to be prohibitive. It has noted that the costs and other factors has led the Mexican decision makers to continue to use their 9.9 MGD treatment capacity for the present. There several options the Mexican government can explore with respect its effluent that goes to the NIWTP. One possibility is to trade the value of its effluent from the NIWTP that is released into the Santa Cruz River for the wastewater treatment bill. Essentially, the Mexican government could be compensated its effluent bill. This raises the question on what methodology should be used to determine the value of the Mexican effluent treated and released to the Santa Cruz River. (Some work has been done on the valuation of effluent water for the Santa Cruz River.) The reduction of effluent flows from the NIWTP to the Santa Cruz River and the likely impact on the ecosystem services provided by the Santa Cruz River has become an important policy question. Norman et al (2013) look at several scenarios that assume reductions in wastewater flow releases to the Santa Cruz River from the NIWTP. This research looks at the land use changes that occur with each scenario. The problem of managing this effluent is one of the important issues to be addressed in our current research.

The second set of water management concerns is the Los Alisos River Basin. This basin is located in Sonora south of the Nogales twin city metropolitan area. The Los Alisos River Basin is hydrologically independent of the Santa Cruz River Basin. (This means that there is no direct interaction between the surface and groundwater resources in these two basins.) The Los Alisos River Basin is important to use for two reasons. First, Nogales, Sonora draws water from well fields in this basin to satisfy its municipal demands. Second, a treatment plant known as the

Los Alisos Wastewater Treatment Plant (LAWTP) has been built and now available for use. The plan is to begin redirecting wastewater flows from the NIWTP to the LAWTP. The treated effluent from the LAWTP will be used for recharging the Los Alisos aquifer where Nogales, Sonora gets part of its water supply. Prichard and Scott (2013) examine the interbasin water and wastewater transfers by Nogales, Sonora. The interbasin water and wastewater transfers are included in our modeling efforts.

3. Static Model Formulation

The purpose of this working paper is to provide an explanation of the static version of our model. In addition, we also exam a set of marginal decision rules that offer some potential for determining a set of pricing rules that are consistent with economic efficiency for the border region.

We first present the basic characteristics of the model structure. This model is designed to capture some of the salient features of the Santa Cruz River Basin. We define two regions for the river basin and use the index r. The portion of the Santa Cruz River Basin in the Mexican state of Sonora is denoted as $r = MX$. The portion of Santa Cruz River Basin in Arizona (and the SCAMA) is denoted as $r = AZ$. Two aquifers are identified for this research. The first aquifer is the Santa Cruz Aquifer which is a shallow aquifer under the Santa Cruz River and spans both sides of the Mexican-U.S. border. The second aquifer is the Los Alisos Aquifer which is outside the Santa Cruz River Basin and is hydrologically independent of the Santa Cruz River Basin. We use the index s to denote the aquifers. The Los Alisos Aquifer is denoted as $s = l$ and the Santa Cruz Aquifer is denoted as $s = S$. We let the indices $i \text{ and } j$ $(i, j = 1, .., 4)$ represent cities in the river basin. In particular, $i = 1$ represents Nogales, Sonora; $i = 2$ represents Nogales, Arizona; $i = 3$ represents Rio Rico, Arizona; and $i = 4$ represents Tubac, Arizona.

The water demands in our model are represented by three sectors: residential, nonresidential; and agriculture. We generalize the agricultural sector by assuming that agricultural activities are aggregated to the regional level, the two regions for our study region being Sonora and Arizona. All of the communities on both sides of the border have both residential and nonresidential demands for water.

We first develop the specifications for the residential demand for water. We assume that there is a typical household of a certain size for each community. We also assume an exogenous number of such households in each community. A total benefit function is specified for each community and is assumed to reflect key characteristics of that community. Let Z_{ir} represent the quantity of water consumed for the typical household in community i located in region r. The total benefit function for the typical household in this case is represented as $B_{ir}(Z_{ir})$ where we assume that $B'_{ir}(Z_{ir}) > 0$ and $B''_{ir}(Z_{ir}) < 0$. Let M_{ir} represent the number of residential households in community i located in region r. For this community, the total benefit of residential water demand is given by $M_{ir}B_{ir}(Z_{ir})$. If B_1 represents the total benefit for all residential water .consumption in the entire Santa Cruz River Basin, we have the following:

$$B_1 = M_{1MX}B_{1MX}(Z_{1MX}) + \sum_{i=2}^{4} M_{iAZ}B_{iAZ}(Z_{iAZ}) \qquad (1)$$

As previously stated, we assume that each community in each region has a nonresidential demand for water. Let each nonresidential used in a community be represented by the index m $(m = 1, \dots, M)$ in regional r. Let X_{mir} represent nonresidential water consumption for user m in community i, region r. Total benefits for nonresidential water consumption in this are defined as $D_{mir}(X_{mir})$. We assume that $D'_{mir}(X_{mir}) > 0$ and that $D''_{mir}(X_{mir}) < 0$. Let B_2 represent total nonresidential benefits of water consumption. Then

$$B_2 = \sum_{m=1}^{M} D_{m1MX}(X_{m1MX}) + \sum_{i=2}^{4}\left[\sum_{m=1}^{M} D_{miAZ}(X_{miAZ})\right] \quad (2)$$

The last set of benefit functions is for agriculture. The benefit functions in this sector are profit functions for agricultural activities that are based on irrigation. The profit function is defined as the profit per unit of land used for each crop. Let the particular type of crop be denoted as k $(k = 1, \dots, K)$, and p_{kr} the exogenous price of crop k in region r. The current formulation for agricultural production in each region is simplified by assuming a Leontief fixed proportion production function. (This can easily be modified to use the Ricardian rent approach based on a positive mathematical programming (PMP) formulation.) Let L_{kr} represent a land variable for crop k in region r, y_{kr} the yield for crop k in region r, and A_{kr} the average cost of production per unit of land for crop k in region r. Also let Π_r represent profits from agricultural production in region r. The profits can be stated as

$$\Pi_r = \sum_{k=1}^{K} (p_{rk} y_{rk} - A_{rk}) L_{rk} \quad (3)$$

Let $\widehat{\Pi}$ represent total profits for agricultural production in our study region. These profits are stated as:

$$\widehat{\Pi} = \Pi_{MX} + \Pi_{AZ} \quad (4)$$

The demand for water for each of the crops produced in our study region has an “amount of water application requirement” per unit of land used to support a particular crop yield. Let the applied water requirement per unit of land be denoted as b_{rk} and also let the total water required for agricultural activities in each region be represented as Q_r. The total water demand for each region is as follows:

$$\sum_{k=1}^{K} b_{MXk} L_{MXk} = Q_{MX} \tag{5}$$

$$\sum_{k=1}^{K} b_{AZk} L_{AZk} = Q_{AZ} \tag{6}$$

The above two relationships represent the total agricultural water demand in each of the subdivisions in our study region, assuming that all agricultural activity in both regions are supported by irrigation. Moreover, irrigation water for both regions only comes from the Santa Cruz Aquifer. The quantities Q_{MX} and Q_{AZ} are assumed to be the amounts of water pumped for agricultural use in each region and come directly from the Santa Cruz Aquifer. Let ε_{ra} represent the pumping cost for groundwater (includes energy, operation, and maintenance cost) from the aquifer in region r plus the cost of allocating irrigation water. Total irrigation cost is $\varepsilon_{ra} Q_r$.

Next we must account for the nonagricultural water allocation. Let X_{ir} represent the nonagricultural water use in community i located in region r. Consider first $r = MX$. Then

$$M_{1MX} Z_{1MX} + \sum_{m=1}^{M} X_{m1MX} = X_{1MX} \tag{7}$$

Next let $r = AZ$, so that the similar relationship in this region is

$$M_{iAZ} Z_{iAZ} + \sum_{m=1}^{M} X_{miAZ} = X_{iAZ} \tag{8}$$

$$(i = 2,3,4)$$

The nonagricultural or municipal demands for water are assumed to be supplied through a municipal water plant facility. Moreover, we assume that the municipal water is pumped from an aquifer and goes through a purification process before it is distributed to the demand units. In the case of Nogales, Sonora, municipal water is taken from two different aquifers: the Santa Cruz Aquifer; and the Los Alisos Aquifer. All of the municipal water for the communities in Arizona is taken from the Santa Cruz Aquifer. Consider first the Santa Cruz Aquifer. We assume that the following communities pump water from the Santa Cruz Aquifer: Nogales, Sonora; Nogales, Arizona; Rio Rico, Arizona; and Tubac, Arizona. In addition, agricultural irrigation water for Arizona is taken from the Santa Cruz River and irrigation water for agricultural activities in Sonora comes from only the Santa Cruz Aquifer. (Currently, irrigation water in Sonora is restricted to the Santa Cruz Aquifer and municipal water for Nogales, Sonora can come from either aquifer.) The options of groundwater for Nogales, Sonora provide some complications for our modeling exercise, so we will specify the groundwater supply sources for Nogales, Sonora first. Let Y_{SMX} represent the amount of water Nogales, Sonora pumps from the Santa Cruz Aquifer and Y_{lMX} be the amount water this city pumps from the Los Alisos Aquifer. The balance equation for municipal water demand in Nogales, Sonora is

$$Y_{SMX} + Y_{lMX} = X_{1MX} \tag{9}$$

The variable X_{SMX} will appear in the balance equation for the Santa Cruz Aquifer and Y_{lMX} will appear in the balance equation for the Los Alisos Aquifer. Let S_S represent the amount of water in the Santa Cruz Aquifer. Then the balance equation (constraint) for the Santa Cruz Aquifer in our model is as follows:

$$Y_{SMX} + \sum_{i=2}^{4} X_{iAZ} + Q_{MX} + Q_{AZ} \leq S_S \tag{10}$$

Let the amount of water in the Los Alisos Aquifer be represented as S_i. The balance equation or constraint for the Los Alisos Aquifer is

$$Y_{lMX} \leq S_l \tag{11}$$

The next set of concepts to develop are the water cost functions for the municipalities. These costs for the Arizona communities include pumping and purification costs. The primary source of water for the Arizona municipalities is the Santa Cruz Aquifer. Let α_{iAZ} represent the energy, operation and maintenance cost plus the water purification treatment cost per unit of water pumped and delivered. The water costs for each Arizona municipality is $\alpha_{iAZ}X_{iAZ}$.

The costs of water for Nogales, Sonora are broken out as follows. First, let μ_{1MX} represent the treatment cost for water purification. The total treatment cost for Nogales, Sonora is $\mu_{1MX}X_{1MX}$. Let θ_{1MX} represent the per unit cost for pumping water from the Santa Cruz Aquifer for municipal water in Nogales, Sonora and η_{1MX} the per unit cost of pumping water from the Los Alisos Aquifer. The respective pumping costs for Nogales, Sonora are $\theta_{1MX}Y_{SMX}$ and $\eta_{1MX}Y_{lMX}$.

In summary, the total costs for water in the Arizona region of our model are as follows:

$$TC_{AZ} = \sum_{i=2}^{4} \alpha_{iAZ}X_{iAZ} + \varepsilon_{AZS}Q_{AZ} \qquad (12)$$

The total costs for water in the Sonora region of our model are as follows:

$$TC_{MX} = \mu_{1MX}X_{1MX} + \theta_{1MX}Y_{SMX} + \eta_{1MX}Y_{lMX} + \varepsilon_{MXS}Q_{MX} \qquad (13)$$

The last modeling task for this document is to represent the municipal wastewater transfers. All of the wastewater flows from Nogales, Arizona are assumed to be transferred to the Nogales International Wastewater Treatment Plant (NITWTP). Wastewater flows from Nogales, Sonora are assumed to be transferred to both the NIWTP and the Los Alisos Wastewater Treatment Plant (LAWTP). Our immediate task is to determine the source and magnitude of wastewater flow that is sent to the LAWTP and the NIWTP. In a consulting study done by Camp, Dresser, and McKee (1997), it was estimated that 70 percent of the municipal water (residential and nonresidential water consumption) reaches the sewer system for the cities of Nogales Sonora and Nogales, Arizona. We adopt this approach and assume that the wastewater flow both of these cities is some fixed proportion of the municipal water consumed in each of the two cities.

Consider first the wastewater flow generated for Nogales, Arizona. Let the variable U_{2AZ} represent the wastewater flow generated in Nogales, Arizona and also let Δ_{2AZ} represent the proportion of municipal water consumed in Nogales, Arizona that reaches the sewer system as wastewater flow. The wastewater flow that is transferred to the NIWTP in this case is given by the following relationship:

$$\Delta_{2AZ} X_{2AZ} = U_{2AZ} \tag{14}$$

We follow the same strategy for determining the wastewater flows generated for Nogales, Sonora. Let Δ_{1MX} represent the portion of municipal water consumed in Nogales, Sonora that reaches the sewer system as wastewater flow. The variable U_{1MX} represents the wastewater flow generated in this case and summarized by the following relationship:

$$\Delta_{1MX} X_{1MX} = U_{1MX} \tag{15}$$

A review of the existing research reports concerning the disposition of wastewater flows in the Nogales twin cities indicates that all wastewater flows generated in Nogales, Arizona are transferred to the NIWTP. The wastewater flows generated in Nogales, Sonora are transferred to the NIWTP and the LAWTP. Let V_{nMX} represent that amount of wastewater flow transferred to the NIWTP and V_{lMX} represent that amount of wastewater flow transferred to the LAWTP. The following relationships are introduced to account for the disposition of the Nogales, Sonora wastewater flows:

$$V_{nMX} + V_{lMX} = U_{1MX} \tag{16}$$

We now turn our attention to the task of developing the important components of the regional wastewater treatment plant cost functions and the related water quality relationship.

ReVelle et al. (1967), McGarity (1997) and Karamouz (2003) provide the foundations for the wastewater treatment cost functions which can be used in a modeling exercise like ours. The approach demonstrated in this body of research focuses explicitly on the treatment efficiency of a wastewater treatment plant where the main pollutant is BOD. The treatment plant efficiency is defined as the amount of BOD removed divided by the BOD originally present. The treatment efficiency is the main decision variable and the volumetric rates of discharge in these types of management model formulation are independent of the pollution removal efficiency rates (McGarity, 1997).

A second approach frequently used to model wastewater treatment costs is to state these costs as a function of both the pollutant removal efficiency and the volume of wastewater flows. For example, this approach has been used in research reported by Hernandez-Sancho and Sala-Garrido (2003), Dinar and Yaron (1986), Loehman et al. (1979), Phillips et al. (1982), and Fraas and Munley (1984). This is the approach we will use in our initial modeling formulations. The decision variable in our situation is assumed to be the volume of wastewater and the plant treatment efficiency is assumed to be given in the statement of the treatment cost function.

Let Γ_{AZ} represent the per unit cost of treating the wastewater flow at the NIWTP. This parameter includes the pollution efficiency removal parameter. Let R_{nAZ} represent the amount of treated effluent released from the NIWTP into the Santa Cruz River. The total cost of wastewater treatment for the NIWTP is given as $\Gamma_{AZ}R_{nAZ}$. Next, let Ω_{lMX} represent the per unit cost of wastewater treatment for the LAWTP. The total cost of wastewater treatment in this case is given as $\Omega_{lMX}V_{lMX}$. These costs are entered into the management model objective function.

The optimization model in its full form is given as follows:

$$
\begin{aligned}
Max \quad & M_{1MX}B_{1MX}(Z_{1MX}) \\
& + \sum_{m=1}^{M} D_{m1MX}(X_{m1MX}) \\
& + \sum_{i=2}^{4} M_{iAZ}B_{iAZ}(Z_{iAZ}) \\
& + \sum_{i=2}^{4}\left[\sum_{m=1}^{M} D_{miAZ}(X_{miAZ})\right] \\
& + \sum_{k=1}^{K}(p_{AZk}y_{AZk} - A_{AZk})L_{AZk} + \sum_{k=1}^{K}(p_{MXk} - A_{MXk})L_{MXk} \\
& - \left[\sum_{i=2}^{4} \alpha_{iAZ}X_{iAZ} + \varepsilon_{AZS}Q_{AZ}\right] \\
& - [\mu_{1MX}X_{1MX} + \theta_{1MX}Y_{SMX} + \eta_{1MX}Y_{lMX} + \varepsilon_{MXS}Q_{MX}] \\
& - [\Gamma_{AZ}R_{nAZ} + \Omega_{lMX}V_{lMX}]
\end{aligned} \tag{17}
$$

Subject to

$$\sum_{k=1}^{K} b_{MXk}L_{MXk} = Q_{MX} \quad (\psi_{MX}) \tag{5}$$

$$\sum_{k=1}^{K} b_{AZk}L_{AZk} = Q_{AZ} \quad (\psi_{AZ}) \tag{6}$$

$$M_{1MX}Z_{1MX} + \sum_{m=1}^{M} X_{m1MX} = X_{1MX} \quad (\lambda_{mx}) \tag{7}$$

$$M_{iAZ}Z_{iAZ} + \sum_{m=1}^{M} X_{miAZ} = X_{iAZ} \quad (\lambda_{iAZ}) \tag{8}$$

$$(i = 2,3,4)$$

$$Y_{SMX} + Y_{lMX} = X_{1MX} \quad (\Lambda_{1MX}) \tag{9}$$

$$Y_{SMX} + \sum_{i=2}^{4} X_{iAZ} + Q_{MX} + Q_{AZ} \leq \bar{S}_S \quad (\pi_s) \tag{10}$$

$$\Delta_{2AZ}X_{2AZ} = U_{2AZ} \quad (\gamma_{2AZ}) \tag{14}$$

$$\Delta_{1MX} X_{1MX} = U_{1MX} \;\; (\gamma_{1MX}) \tag{15}$$

$$V_{nMX} + V_{lMX} = U_{1MX} \;\; (\Phi_{1MX}) \tag{16}$$

$$Y_{lMX} - V_{lMX} \leq \bar{S}_l \;\; (\pi_l) \tag{18}$$

$$U_{2AZ} + V_{nMX} = R_{nAZ} \;\; (\rho_{AZ}) \tag{19}$$

$$R_{nAZ} \geq \bar{R}_{nAZ} \;\; (\Psi_{nAZ}) \tag{20}$$

Constraint (18) is a constraint on the amount of water pumped from the Los Alisos Aquifer. The variable Y_{lMX} represents the amount of water pumped from the aquifer while V_{nMX} represents the amount of treated wastewater from the LAWTP that is returned to the Los Alisos Aquifer in the form of recharge. Constraint (19) is a balance equation for the amount of wastewater flows transferred to the NIWTP from Nogales, Arizona and Nogales, Sonora. Water quality for the Santa Cruz River is represented by a minimum return flow from the NIWTP as shown in constraint (20). The variables in parentheses for the constraints are the corresponding Lagrangean multipliers for each constraint.

4. Marginal Decision Rules

Efficient management of water resources frequently leads to the call for policies based on marginal cost pricing or what we will call spot market pricing (Zarnikau, 1994). The prices charged under spot market pricing accurately reflect all of the marginal opportunity costs of allocating water resources efficiently in a river basin. We examine spot market pricing in the context of our model for the Santa Cruz River Basin in the border region of the twin cities of Nogales, Arizona-Nogales, Sonora. The model developed in the previous section is designed to maximize the net economic benefits allocating water resources in the entire study region.

The first task in our analysis is to consider the allocation of water in our study region that is taken from the Santa Cruz Aquifer. The constraint for the water pumped from this aquifer for all uses in our study region is constraint (10) and the corresponding shadow price is π_S. We can interpret π_S as a "supply price" for water taken from the Santa Cruz Aquifer.

Consider first the use of water for irrigating agriculture in the Arizona region of our study area. It can be shown that the marginal decision rule for optimal water application to crop k in the Arizona region is the following:

$$\pi_s = \frac{(p_{AZk}y_{AZk} - A_{AZk})}{b_{AZk}} - \varepsilon_{AZS} \qquad (21)$$

$$(k = 1, \dots, K)$$

The first term on the right hand side of equation (21) represents the marginal return per unit of irrigation water applied to a unit of land for crop k in Arizona. Dividing by the coefficient b_{AZk} converts this term to a marginal return for a unit of water applied to applied to crop k. The term ε_{AZk} is the per unit cost irrigation cost. Thus, the right hand side of this equation represents the marginal net return to irrigation water applied to crop k in Arizona. Moreover, optimal water allocation for irrigating crop k in Arizona is characterized by the marginal net return to irrigation water being equal to the supply price of water taken from the Santa Cruz Aquifer.

We next consider the use of water for irrigation in the Sonora region that comes from the Santa Cruz River. This marginal decision rule for optimal water application to crop k in the Sonora region is the following:

$$\pi_s = \frac{(p_{MXk}y_{MXk} - A_{MXk})}{b_{MXk}} - \varepsilon_{MXS} \qquad (22)$$

$$(k = 1, \dots, K)$$

Equation (22) is similar to equation (21). Moreover, the interpretations for equation (21) are identical to those that apply to equation (23) and are not repeated here.

The second water use category is municipal water demand which is further classified as residential demand and nonresidential demand. (The nonresidential demand includes both commercial and industrial water demand in this research.) The total municipal water use for each Arizona municipality is denoted as X_{iAZ} $(i = 2,3,4)$. For each Arizona municipality, the municipal allocation of water for community i is shown by balance equation (8) while the total municipal demand for the Arizona communities appears in the Santa Cruz Aquifer constraint (8). The shadow price for balance constraint (8), λ_{iAZ}, and constraint (10), π_S, are important to our analysis.

We consider first the Arizona municipalities Rio Rico and Tubac $(i = 3.4)$. The respective marginal decision conditions for residential water use and nonresidential water use are the following:

$$\frac{\partial B_{iAZ}}{\partial Z_{iAZ}} = \lambda_{iAZ} \tag{23}$$

$$(i = 3,4)$$

$$\frac{\partial D_{miAZ}}{\partial X_{miAZ}} = \lambda_{iAZ} \tag{24}$$

$$(m = 1, \dots, M)$$

$$(i = 3,4)$$

Clearly, λ_{iAZ} represents the marginal benefit of municipal water use in each community$(i = 3,4)$. Moreover, this shadow price facilitates the achievement of an efficient allocation of municipal water use between residential and nonresidential water uses. We will refer to λ_{iAZ} as the marginal benefit of municipal water use. We can also think of this shadow price as a "demand allocation price."

The optimal allocation of water to each Arizona community i $(i = 3.4)$ is based on the following marginal decision rule:

$$\pi_S = \lambda_{iAZ} - \alpha_{iAZ} \tag{25}$$

$$(i = 3,4)$$

The term α_{iAZ} is the per unit cost of providing water in community i for municipal use. The right hand side of equation (25) represents the marginal net benefit of municipal water use in community $(i = 3,4)$. We can conclude from equation (25) that the optimal allocation of water from the Santa Cruz Aquifer to Arizona community i $(i = 3,4)$ requires that the marginal water supply price π_S be equal to the marginal net benefit of municipal water use.

Nogales, Arizona $(i = 2)$ also gets all of its water for municipal use from the Santa Cruz Aquifer. The marginal decision rule for the optimal allocation of municipal water to Nogales, Arizona is the following:

$$\pi_s = \lambda_{2AZ} - \alpha_{2AZ} - \Delta_{2AZ}(\Gamma_{2AZ} + \Psi_{2AZ}) \tag{26}$$

We focus our discussions here on the right hand side of equation (26). First, the shadow price λ_{2AZ} represents the marginal benefit of municipal water use in Nogales, Arizona and α_{2AZ} is the per unit of municipal water in Nogales, Arizona. A certain proportion of the municipal water use in Nogales, Arizona is transferred to the NIWTP for treatment and release into the Santa Cruz River. In addition, we have assumed in our model that there are likely to be minimum release requirements that are deemed necessary to maintain some level of environmental quality in the Santa Cruz River downstream from point of releases. There are two costs that must be accounted for in this situation. First, Γ_{2AZ} represents the per unit treatment cost at the NIWTP. Second, the shadow price Ψ_{2AZ} represents the marginal opportunity cost of a binding minimum release requirement that must be accounted for the release of treated effluent to the Santa Cruz River.

We can conclude the following with respect to equation (26). First, the right hand side of this equation represents the marginal net benefit for municipal water use in Nogales, Arizona when the water source is the Santa Cruz Aquifer. In this case, the wastewater flows which are assumed to be a proportion of municipal water use are transferred to the NIWTP to be treated and released to the Santa Cruz River. In addition, there may be a environmentally mandated minimum flow release from the NIWTP. The third term on the right hand side of equation (26) represent these additional marginal opportunity costs. We can conclude from this discussion that the optimal allocation of municipal water for Nogales, Arizona which is taken from the Santa Cruz Aquifer requires that the marginal supply price of water π_s must be equal to marginal net benefit for municipal water use.

We next consider the municipal demand for water in Nogales, Sonora. The respective marginal decision rules for residential water use and nonresidential water use are the following:

$$\frac{\partial B_{1MX}}{\partial Z_{1MX}} = \lambda_{1MX} \tag{27}$$

$$\frac{\partial D_{m1MX}}{\partial X_{m1MX}} = \lambda_{1MX} \tag{28}$$

$$(m = 1, \ldots, M)$$

We can consider λ_{1MX} to be a "demand allocation price" for municipal water use in Nogales, Sonora. This shadow price can also be interpreted as the marginal benefit of municipal water use in Nogales, Sonora.

We now turn our attention to the supply of water for municipal use in Nogales, Sonora. The analysis for this situation is complicated by the fact that the municipal water comes from two different sources, namely, the Santa Cruz Aquifer which is located on both sides of the border and the Los Alisos which is located roughly 25 miles south of Nogales, Sonora in Mexico. Matters are further complicated by the fact that the wastewater flows generated by municipal water use in Nogales, Sonora can be transferred to the NIWTP, the LAWTP, or a combination of both. We consider a set different possible situations with respect to the source of municipal water supply and where the wastewater flows are transferred.

The following observations provide a helpful starting point for our analysis. First, the supply of municipal water for Nogales, Sonora that is taken from the Santa Cruz Aquifer is denoted as Y_{SMX} and appears in constraint (10). The shadow price for this constraint is π_S. The amount of municipal water supply taken from the Los Alisos is denoted as Y_{lMX} and appears in constraint (14) where the constraint shadow price is π_l. Both of these variables appear in the balance equation (9) showing that municipal water supply for Nogales, Sonora is restricted to these two sources. The shadow price for equation (9) is Λ_{1MX}.

We first consider the situation where the municipal water supply source for Nogales, Sonora is the Santa Cruz Aquifer and wastewater flows are transferred to the NIWTP. The marginal decision rule for this situation is

$$\pi_s = \lambda_{1MX} - \theta_{1MX} - \mu_{1MX} - \Delta_{1MX}(\Gamma_{2AZ} + \Psi_{2AZ}) \tag{29}$$

As argued previously, π_S represents the supply price for water taken from the Santa Cruz Aquifer. The right hand side of equation (29) is the marginal net benefit of municipal water use for Nogales, Sonora which is taken from the Santa Cruz Aquifer and the corresponding wastewater flows are transferred to the NIWTP. As previously concluded, the shadow price λ_{1MX} is the marginal benefit of municipal water use in Nogales, Sonora. The remaining terms on the right hand side of this equation represent different types of marginal opportunity costs. The term θ_{1MX} is the per unit cost of pumping water from the Santa Cruz Aquifer for municipal water use in Nogales, Sonora while μ_{1MX} is the per unit treatment cost of this water. The last term is concerned with the portion of the municipal wastewater flow that is transferred to the NIWTP and captures two types of costs. First, Γ_{2AZ} represents the per unit treatment cost at the NIWTP. Second, the shadow price Ψ_{2AZ} is the marginal opportunity cost of a binding minimum release treated effluent requirement to the Santa Cruz River that must be met. In conclusion, the optimal allocation of water taken from the Santa Cruz Aquifer for municipal use in Nogales, Sonora requires that the marginal supply price π_S must be equal to the marginal net benefit of this use. The latter must include an accounting of the marginal treatment cost at the NIWTP plus the marginal opportunity cost of a binding minimum flow release constraint for treated effluent releases to the Santa Cruz River.

The next option to consider for Nogales, Sonora assumes that the water for municipal use is taken from the Santa Cruz Aquifer and part of the wastewater flows are transferred to the LAWTP and the treated effluent is then used as recharge to the Los Alisos Aquifer. The marginal decision rule for this option is

$$\pi_S = \lambda_{1MX} + \Delta_{1MX}\pi_l - \theta_{1MX} - \mu_{1MX} - \Delta_{1MX}\Omega_{1MX} \tag{30}$$

As before, the left hand side of equation is the supply price of water taken from the Santa Cruz Aquifer, π_S. The right hand side of this equation is the marginal net benefit for this option. If we compare equation (30) with equation (29), we find several similarities, but there are also some noticeable differences. First, the expression $\Delta_{1MX}\Omega_{1MX}$ is the per unit cost of treating the wastewater flows transferred to the LAWTP. The variable π_l is the shadow price of the constraint for the Los Alisos Aquifer and can be interpreted as the supply price of water taken from this aquifer. Thus, the expression $\Delta_{1MX}\pi_S$ represents the marginal benefit for recharging the Los Alisos Aquifer with the treated effluents from the LAWTP. The net marginal benefit here also includes the marginal benefit of municipal use of water. Once again, the marginal supply price of water taken from the Santa Cruz Aquifer must be equal the marginal net benefit of municipal water used for the optimal outcome.

We now examine the option of taking water from the Los Alisos Aquifer for municipal use in Nogales, Sonora and transferring the wastewater flows from this use to the NIWTP. The marginal decision rule in this case is

$$\pi_l = \lambda_{1MX} - \eta_{1MX} - \mu_{1MX} - \Delta_{1MX}(\Gamma_{2AZ} + \Psi_{2AZ}) \qquad (31)$$

The water supply price for this case is π_l which is the shadow price associated with the model constraint for the Los Alisos Aquifer. As noted previously, λ_{1MX} represents the marginal benefit of municipal water use in Nogales, Sonora. The term η_{1MX} is the per unit pumping cost for water taken from the Los Alisos Aquifer and μ_{1MX} is the per unit treatment cost for municipal water in Nogales, Sonora. The last expression on the right hand side of equation (31) represents the full marginal opportunity cost associated with transferring wastewater flows to the NIWTP. Optimal allocation of water from the Los Alisos Aquifer for municipal use for this option requires that the Los Alisos Aquifer water supply price equal the marginal net benefit of municipal water use in Nogales, Sonora.

The last option to consider for municipal water use in Nogales, Sonora takes water from the Los Alisos Aquifer and transfers the related wastewater flows to the LAWTP. The marginal decision rule for this case is

$$\pi_l = \lambda_{1MX} + \Delta_{1MX}\pi_l - \eta_{1MX} - \mu_{1MX} - \Delta_{1MX}\Omega_{1MX} \qquad (32)$$

The first term on the left hand side of equation (32) is the supply price of water taken from the Los Alisos Aquifer. The right hand side of this equation is marginal net benefit of municipal water use in Nogales, Sonora and consists of the following components. First, λ_{1MX} is the marginal benefit of municipal water use in Nogales, Sonora and $\Delta_{1MX}\pi_l$ is the value of the treated effluent from the LAWTP that is used for recharge into the Los Alisos Aquifer. The term η_{1MX} is the per unit cost of pumping water from the Los Alisos Aquifer, μ_{1MX} is the per unit treatment cost of water for municipal uses and $\Delta_{1MX}\Omega_{1MX}$ is the per unit cost of wastewater treatment at LAWTP. Once again, optimal use of water taken from the Los Alisos Aquifer for municipal use in Nogales, Sonora requires that the supply price of water from the Los Alisos Aquifer equal the marginal net benefit of this use as shown in equation (32).

The last question to examine is the relationship between the water supply prices for the two aquifers. This relationship is given by the following

$$\pi_S - \pi_l = \eta_{1MX} - \theta_{1MX} \tag{33}$$

The term η_{1MX} is the per unit cost of pumping water from the Los Alisos Aquifer and θ_{1MX} is the per unit cost of pumping water from the Santa Cruz Aquifer.