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Game Theory Analysis of Competition for Groundwater Involving El Paso, Texas and Ciudad Juarez, Mexico

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Abstract

We examine the potential gains from cooperation in the withdrawal of water from the Hueco Bolson aquifer that provides municipal water supply for El Paso, Texas and Ciudad Juarez, Mexico. The aquifer lies beneath the international border, and both cities operate independently regarding pumping rates and withdrawals. We estimate the gains by comparing four scenarios in a dynamic setting: 1) a status quo scenario in which both cities continue extracting groundwater as they are at present, 2) a Nash non-cooperative game scenario, 3) a Nash bargaining scenario, and 4) a scenario that involves maximizing the sum of net benefits in both cities. All scenarios, including the non-cooperative game, provide a longer useful life of the Hueco Bolson aquifer than does the status quo. In the Nash bargaining scenario, both cities gain from cooperation and the sum of net benefits approaches the maximum that can be obtained by maximizing that value explicitly.

Key Words: Groundwater, transboundary resources, game theory, Nash bargaining

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Introduction

El Paso, Texas and Ciudad Juarez, in the state of Chihuahua, Mexico are located on the Rio Grande River, which forms a portion of the international border between the United States and Mexico. Since the early 1900s, most of the surface water flowing in the southern Rio Grande has been allocated to agricultural users in both countries. As a result, both El Paso and Juarez have relied primarily on groundwater resources to meet municipal and industrial water demands. In particular, both cities have obtained large portions of their water supply from the Hueco Bolson aquifer, which extends across the international border (Day, 1975, 1978; Armstrong, 1982; Earl and Czerniak, 1996).

Annual withdrawals from the Hueco Bolson have exceeded natural recharge rates for many years, causing a persistent decline in the volume of water stored in the aquifer (Charbeneau, 1982). Since 1940, water tables have declined by more than 50 feet at many of the municipal wellfields serving El Paso and Juarez (Texas Water Development Board, 1997). Some authors suggest that the recoverable supply of water in the Hueco Bolson will be exhausted at some time between 2005 and 2030, if current pumping rates are maintained (Eaton and Andersen, 1987, p. 53; Kuo, 2000; Paso del Norte Water Task Force, 2001;). When depletion occurs, the cost of satisfying municipal and industrial water demands in the two cities will increase substantially, as replacement supplies must be imported from distant aquifers or purchased from farmers willing to sell or lease a portion of their surface water supply.

The cost of maintaining water quality in municipal water supplies also may increase

with continued drawdown of the Hueco Bolson aquifer. The salinity of water remaining in the aquifer increases as the volume becomes smaller, and cones of depression caused by excessive pumping may cause salts to move from mud interbeds, degrading groundwater quality (Hibbs, 1999). In addition, contaminants may enter the Hueco Bolson in cross-formational flows of water from the Rio Grande aquifer, as the gradient between the two aquifers increases with cumulative withdrawals from the Hueco Bolson (Hibbs and Boghici, 1999).

Water demands have increased in El Paso and Juarez in recent years with increasing populations and economic growth stimulated in part by the North American Free Trade Agreement (Ganster et al., 2000; Peach and Williams, 2000; Clement et al., 2002). Recognizing the challenge of providing water supply in future, El Paso began developing alternative water sources by leasing irrigation water rights from property owners in El Paso County in the 1960s (Day, 1978; El Paso Water Utilities, 1999). Water conservation programs including rebates for acquiring water-saving appliances and a water pricing structure that discourages excessive use have been implemented since the early 1990s (Bath et al., 1994). As a result, the average per capita consumption of water has declined in El Paso and the city has reduced its withdrawals from the Hueco Bolson, while increasing its use of surface water. Per capita incomes and water consumption are much lower in Juarez, but the population is larger and growing more rapidly (Zwerneman, 1977). Juarez has increased its withdrawals from the Hueco Bolson in recent years, while not yet developing alternative water supplies (Chavez, 2000).

The Hueco Bolson aquifer will be depleted in the near future if both cities continue to extract groundwater at current rates or if they increase annual withdrawals to satisfy rising municipal and industrial demands. Depletion of the aquifer may be inevitable, but it may not be optimal from an economic perspective, as there may be value in maintaining water in the aquifer to provide municipal supply in years when surface supplies are reduced by drought conditions. If depletion is optimal, the present value of future costs of

providing water supply will vary with the year in which depletion occurs and with alternative rates of groundwater withdrawal in the interim.

Depletion of the Hueco Bolson may occur more quickly than is optimal because neither El Paso nor Juarez has an exclusive right to extract water from the aquifer. Hence, neither city has a clear economic incentive to consider the marginal user cost imposed on the other city when determining how much water to withdraw each year. As a result, the sum of annual withdrawals likely will exceed the socially optimal withdrawal in most years and the present value of net benefits will not be maximized over time.

El Paso and Juarez may gain financially by implementing a cooperative water management program in which the cities seek to achieve the optimal use of surface and groundwater resources to provide water supply in future. Such a program may involve coordinated development of alternative surface and groundwater resources, and agreements regarding annual withdrawals and the volume of water to be maintained in the Hueco Bolson, in perpetuity. The potential gains to both cities may include reductions in uncertainty and lower costs of providing water supply in future.

The goal of this paper is to describe the potential gains to both cities from cooperating in their use of surface and groundwater resources to satisfy municipal and industrial water demands. We estimate the gains by comparing four scenarios in a dynamic setting: 1) a status quo scenario in which both cities continue extracting groundwater as they are at present, 2) a Nash non-cooperative game scenario, 3) a Nash bargaining scenario, and 4) a scenario that involves maximizing the sum of net benefits in both cities. All scenarios, including the non-cooperative game, provide a longer useful life of the Hueco Bolson groundwater reserve than does the status quo. In the Nash bargaining scenario, both cities gain from cooperation and the sum of net benefits approaches the maximum that can be obtained by maximizing that value explicitly.

Conceptual Framework

Withdrawal of water from the Hueco Bolson by El Paso and Juarez can be viewed as a dynamic game in which the two cities may compete or cooperate when choosing the volume of water to extract over time. The potential gains from cooperation include reducing the negative impacts of externalities involving pumping costs and depletion of a nonrenewable resource. The pumping cost externality arises because the withdrawal of water by either city lowers the level of water in the aquifer, causing the cost of pumping to increase for both cities. The depletion externality arises because annual withdrawals greatly exceed natural recharge, and the groundwater likely will be depleted in the near future. Hence, each unit of water removed by either city imposes a marginal user cost on both cities because that water will not be available again in the future.

In the absence of well-defined property rights to a portion of the aquifer, neither El Paso nor Juarez has an economic incentive to consider the pumping cost externality or the marginal user cost it imposes on the other city when withdrawing water from the aquifer. Pumping decisions based only on direct marginal costs and current marginal benefits of groundwater will not be optimal from the perspective of a social planner seeking to maximize the sum of net benefits generated with Hueco Bolson water in both cities, over time. As a result, the resource will be extracted more quickly and depletion will occur sooner than is optimal as viewed from the broader, social perspective.

Pumping cost and resource depletion externalities arise often when groundwater and other open access resources are not allocated or priced appropriately to maximize social or public net benefits. A third externality arises when individuals or cities compete strategically to gain access and obtain use of a scarce resource. In a game theory context, the strategies employed by one player to gain greater access or use than other players may generate costs and activities that would not be undertaken in the absence of strategic competition. For example, one city might install larger pumps and withdraw water more

quickly than otherwise, simply because it is competing with the other city for use of the limited groundwater resource. In the extreme, one city might construct storage facilities within its boundaries in which it could store groundwater extracted long before it is needed. Such a pumping and hoarding strategy would generate direct costs and marginal user costs that could greatly reduce the social net benefits obtained from the limited groundwater.

The policy relevance of negative externalities involving open access groundwater resources often is a function of physical parameters describing an aquifer and economic parameters describing supply and demand characteristics. For example, the gains in social net benefits achieved by regulating a very large, open access aquifer where pumping costs do not increase with declining water levels may be too small to justify policy intervention (Gisser and Sanchez, 1980; Allen and Gisser, 1984). By contrast, regulation of pumping rates or taxation of volumes withdrawn may generate substantial net benefits when aquifers are small, when pumping costs increase with declining stock, or when social rates of time preference are low (Brill and Burness, 1994).

Policy issues regarding the competition for groundwater and the allocation of surface water are particularly challenging in the El Paso/Juarez region, as both resources are limited in supply and both move across the international border. While a treaty has guided the allocation of surface water for many years, no similar agreement has been reached regarding groundwater. The two cities have not developed a coordinated strategy regarding groundwater, although they have begun sharing information regarding withdrawals and aquifer characteristics in recent years (Chavez, 2000; Hume, 2000). The potential gains to greater cooperation may be substantial for both cities, given their relatively low per capita incomes, the high cost of obtaining alternative water supplies, and the high rate of population growth in Juarez.

Empirical Model

Municipal water deliveries in the region are managed by the El Paso Water Utilities (EPWU) and the Junta Municipal de Agua y Saneamiento de Ciudad Juarez (JMAS). The long-term goal of each agency might be described as minimizing the present value of the costs of providing municipal water supplies. The annual cost of water delivery will vary with the costs of water obtained from different supply sources, such as the Hueco Bolson, other aquifers, and surface water sources. The long-term goal can be described also as maximizing the present value of net benefits from water deliveries over time. Demand curves describing the marginal benefits of water consumption are needed when constructing an empirical model in which net benefits are maximized.

True demand curves for water deliveries are not available for El Paso and Juarez. However, the marginal benefit of groundwater can be estimated by considering the cost of obtaining the surface water that would be needed to satisfy municipal water demands if groundwater were not available. At present, the per-unit cost of pumping groundwater from the Hueco Bolson is less than the per-unit cost of obtaining and treating surface water. Hence, one component of the incremental benefit of pumping groundwater is the avoided cost of using surface water. That is the approach we implement in this study.

El Paso has developed several sources of surface water supplies, at prices ranging from \$15 to \$200 per acre-foot. Juarez has not yet developed alternative sources, but we assume that the cost will be higher in Juarez, given that Mexico has a smaller allocation of surface water from the Rio Grande than does Texas. We use these estimates of surface water prices to develop marginal benefit curves for groundwater in both cities. In addition, we consider the current cost of groundwater pumping and the observed rate of pumping in each city when selecting intercept and slope coefficients for the marginal benefit curves.

The per-unit cost of obtaining water from the Hueco Bolson will increase, over

time, as the volume of water remaining in the aquifer declines. Hence, the volume of water withdrawn from the aquifer each year generates both a current cost and a long-term cost by causing higher pumping costs in future. In addition, the volume of water withdrawn by either city has an impact on future pumping costs for both cities. This interaction is described by per-unit pumping costs that increase with pumping lift, as the volume of water remaining in the aquifer is reduced.

Our empirical specification of the net benefits from groundwater pumping in each city is the following:

$$NB_{i,t}(h_t, w_{i,t}) = a_i w_{i,t} + \frac{b_i}{2} w_{i,t}^2 - c_i h_t w_{i,t}$$

where: $NB_{i,t}$ is the net benefit in city i , in year t , h_t is the pumping lift, in feet, $w_{1,t}$, and $w_{2,t}$, are the volumes of water withdrawn by El Paso and Juarez in acre-feet per year, c_i is the per-unit cost of pumping groundwater, in dollars per acre-foot, and $a_{i,t}$ and b_i are coefficients of the marginal benefit functions. The initial values of $a_{i,t}$ and the values of b_i are shown for both cities in Figure 1. We simulate higher populations in future by shifting the marginal benefit functions outward over time using higher values of the vertical intercept parameters $a_{i,t}$.

The value of c_i is determined by the per-unit cost of energy and pump efficiency parameters. We use a value of \$0.10 per acre-foot, per foot of lift, and our initial pumping lift is 400 feet. Hence, the initial pumping cost is \$40.00 per acre-foot.

The state equation governing changes in the pumping lift, over time, involves the sum of withdrawals from the aquifer by both cities, and is given by:

$$h_{t+1} = h_t + \alpha(w_{1,t} + w_{2,t}) - \beta$$

where: α is determined by the area and specific yield of the aquifer and
 β is determined by annual recharge and aquifer characteristics.

Estimates of natural recharge to the Hueco Bolson range from 6,000 to 28,000 acre-feet per year (Turner et al., 2002). We use an estimate of 9,000 acre-feet per year in this study.

Analysis

We examine four scenarios that describe water withdrawals from the Hueco Bolson by El Paso and Ciudad Juarez. All scenarios are dynamic, due to the impact of current extractions on pumping lifts in future. We examine first a status quo scenario in which both cities maintain current groundwater pumping programs. El Paso maintains a constant rate of withdrawal, while Juarez increases its withdrawals to meet the demands of its rising population. We examine also a non-cooperative game scenario in which both cities consider explicitly the impact of cumulative withdrawals on the per-unit cost of pumping groundwater and they choose annual withdrawals by equating marginal costs and benefits. The non-cooperative game scenario involves slower rates of extraction and greater net benefits than the status quo scenario because withdrawals are reduced as the marginal cost of pumping increases. The Nash bargaining scenario describes how both cities can increase their net benefits through cooperation. The sum of net benefits obtained in the Nash bargaining scenario approaches the sum that can be obtained by choosing extraction paths to maximize the sum of net benefits in both cities.

Status Quo Groundwater Pumping

In the first scenario we assume that El Paso will extract 60,000 acre-feet of groundwater each year, while it develops surface water supplies to accommodate increases in demand due to rising population and income levels. By contrast, we assume that groundwater pumping by Juarez will increase steadily, over time, to match increasing demands, given that an alternative surface water supply has not yet been developed. This assumption is implemented by allowing the marginal benefit curve for groundwater in Juarez to shift outward by 2.33% per year. This is not an optimization scenario because we do not require that the marginal benefit of groundwater equals the marginal pumping cost. The scenario simply describes what the future might look like of the two cities extract groundwater to meet their future water requirements, with no concern for determining optimal cooperative or non-cooperative strategies.

If both cities continue to implement their current pumping programs, the aquifer will essentially be depleted in 18 years, given our empirical estimates of aquifer volume, specific yield, and annual recharge. The present values of net benefits obtained from groundwater pumping in that scenario are \$9.05 million in El Paso and \$75.05 million in Juarez (Table 1). The net benefits are much higher in Juarez, given its higher population and pumping rates and its higher cost of obtaining surface water as an alternative to groundwater. In year 18, the volume remaining in the aquifer is just 121,000 acre-feet, the pumping lift is 1,374 feet, and the marginal cost of pumping is \$131 per acre-foot.

Non-Cooperative Game Scenario

The non-cooperative game differs substantially from the status quo scenario. In the game scenario, both Juarez and El Paso choose annual withdrawals to maximize their individual net benefits, subject to information regarding the volume withdrawn by the other city. The dynamic game theory model includes two objective functions and two first-order necessary conditions that are solved simultaneously in each time period. We use backward induction to solve for the complete time path of optimal extractions for each city in the dynamic game theory model. The objective functions in the model are the following:

$$\max_{\{w_{i,t}\}_{t=1}^T} \sum_{t=1}^T \rho^t NB_{i,t}(h_t, w_{i,t})$$

subject to:

$$h_{t+1} = h_t + \alpha(w_{1,t} + w_{2,t}) - \beta$$

$$w_{i,t} \geq 0$$

where: ρ is a discount rate and i takes the values of 1 for El Paso and 2 for Juarez. We use a discount rate of 0.05 in the first set of scenarios.

We construct a recursive algorithm using Maple, a mathematical software product, to solve this set of functional equations using dynamic programming. The results we obtain maximize the present value of net benefits for each city, given the volumes withdrawn by the other city. Hence, the time paths represent a dynamic Nash equilibrium. In addition, the solution is subgame perfect because we have obtained it using backward induction (Selten, 1975; Petit, 1990). The recursive equation describing this dynamic programming

problem is the following:

$$J_{i,t}(h_t) = \max_{w_i} \{NB_{i,t} + \rho(J_{i,t+1}^*(h_t))\}$$

where: $J_{i,t}$ is the optimal discounted present value of net benefits as viewed from year t and looking forward in time.

The net benefit curves for both cities shift outward over time, to reflect increases in population and income levels. In particular, the intercepts of the net benefit curves increase by 1.07% and 2.33% each year in El Paso and Juarez, given that population is growing at estimated rates of 1.5% and 3.0%. We examine 25-year scenarios in this analysis, because most of the water will be withdrawn during that time, even with cooperation, given the increasing demands in both cities and the high per-unit cost of obtaining and treating surface water supplies.

The goal of net benefit maximization causes both cities to extract groundwater more slowly in the non-cooperative game scenario than in the status quo scenario. As a result, 205,000 acre-feet remain in the aquifer at the end of 25 years (Table 1). The pumping lift increases to 1,351 feet and the cost of pumping rises to \$131 per acre-foot. These ending conditions are similar to those in the status quo scenario, but the aquifer has remained viable for seven years longer in the non-cooperative game scenario. In addition, the sum of net benefits is almost twice that obtained in the status quo scenario.

Nash Bargaining

The Nash bargaining solution is determined by maximizing a mathematical product that contains a point in the region of feasible combinations of net benefits for the two cities. That point is called the "threat point" because it represents a default position for

both parties if negotiations leading to a bargaining solution are not successful. The Nash bargaining solution is identified by maximizing the product of distances from the threat point to an alternative point on the frontier of the feasible region. Axioms that characterize the Nash bargaining solution require that both parties gain when moving away from the threat point and that symmetric parties will move away from the threat point in symmetric fashion. We determine the Nash bargaining solution for groundwater pumping from the Hueco Bolson by choosing the values of J_1 and J_2 that maximize the following product:

$$\max[J_1 - J_1^{Th}][J_2 - J_2^{Th}]$$

The net benefit values obtained in the non-cooperative game scenario represent the threat point (J_1^{Th} , J_2^{Th}) in the Nash bargaining solution. Hence, the values of J_1^{Th} and J_2^{Th} in the equation shown above are \$25.0 million for El Paso and \$140.1 million for Juarez. The Nash bargaining solution we obtain shows clearly that both cities gain by cooperating and moving away from the Nash threat point. In particular, the net benefits increase by 3.8% for El Paso and by 1.3% for Juarez (Table 1). The sum of net benefits increases from \$165.1 million to \$167.8 million, an increase of 1.7%. Much of the gain in net benefits is made possible by lower pumping costs, as the pumping lift increases more slowly in the cooperative bargaining scenario. In year 25, the pumping lift is 1,277 feet and the marginal cost of pumping is \$123 per acre-foot. The volume remaining in the bargaining scenario is 471,000 acre-feet, or more than twice the volume remaining in the non-cooperative game scenario.

Maximizing the Sum of Net Benefits

This scenario describes the problem of a social planner whose goal is to allocate water between the two cities in a manner that maximizes the sum of net benefits obtained, over time. The results provide an upper bound estimate of the net benefits that may be obtained with limited water resources, and an additional benchmark for evaluating the gains achieved through cooperation. The objective function involves the summation of net benefits, NB_i , in the two cities, over time:

$$\max_{\{w_{1,t}\}_{t=1}^T, \{w_{2,t}\}_{t=1}^T} \sum_{t=1}^T \sum_{i=1}^2 \rho^t NB_{i,t}(h_t, w_{i,t})$$

subject to:

$$h_{t+1} = h_t + \alpha(w_{1,t} + w_{2,t}) - \beta$$

$$w_{i,t} \geq 0$$

The results obtained when maximizing the sum of net benefits in this problem are similar to those obtained in the Nash bargaining scenario. The present value of the sum of net benefits is \$169.05 million, which is just 0.7% greater than the sum obtained with Nash bargaining (Table 1). There are 487,000 acre-feet remaining in the aquifer in year 25, which is 3.4% greater than the Nash bargaining volume. The net benefits in Juarez actually are higher in this scenario than with Nash bargaining, while the net benefits in El Paso are lower. A larger proportion of groundwater pumping is allocated to Juarez in this scenario, given its larger population and its higher per-unit cost of obtaining an alternative surface water supply.

Discussion

Useful Life of the Hueco Bolson

The current rates of groundwater pumping by El Paso and Ciudad Juarez are not sustainable. The status quo scenario suggests that the Hueco Bolson will be depleted in 18 years if current extraction programs are continued. This estimate is a function of the parameter values used in this analysis and it may over-estimate the length of time during which Juarez will have affordable access to the Hueco Bolson aquifer. Some authors have suggested that the portion underlying Juarez will be depleted within 5 to 10 years if current pumping rates are maintained.

The useful life of the groundwater reserve and the net benefits obtained by using groundwater are much higher in both the non-cooperative and cooperative scenarios. In the non-cooperative game, both cities reduce their rates of withdrawal as the per-unit cost of pumping increases over time. A criterion requiring that marginal benefits equal marginal pumping costs is not imposed in the status quo scenario. Hence, the cities can gain substantial benefits by equating marginal costs and benefits, even if they compete for the limited resource, provided that an alternative surface water supply is available. If it is not, the sum of net benefits is relatively small and the useful life of the resource is quite short.

Time Paths of Annual Withdrawals

Both El Paso and Juarez withdraw groundwater at a faster rate in the non-cooperative game scenario than in either the Nash bargaining or the joint maximization scenario. In particular, annual withdrawals by Juarez increase from 85,000 to 160,000 acre-feet over time in the non-cooperative game scenario, while they begin at only 65,000 acre-feet if a Nash bargaining agreement is implemented (Figure 2). Similarly, annual withdrawals by El Paso decline from more than 40,000 acre-feet in the non-cooperative

game scenario, while they start at only 35,000 acre-feet in the Nash bargaining solution. A program to maximize the present value of the sum of net benefits in both cities would allow Juarez to withdraw more water per year than it would in the Nash bargaining scenario, while the same program would require El Paso to withdraw less water than in the Nash bargaining scenario.

The Sum of Net Benefits

The sum of net benefits in the Nash bargaining scenario is greater than the sum obtained in the non-cooperative game scenario. The proportional increase is only 1.7%, reflecting perhaps the relative inelasticity of demand in pertinent portions of the marginal benefit curves for the two cities. That is, given the relatively high cost of replacement with surface water, groundwater has a substantial incremental value to both cities. Annual withdrawals are relatively high in both the non-cooperative and bargaining scenarios. In addition, most of the present value from cooperation is obtained in the early years. The life of the groundwater reserve is extended with cooperation, but the present value of that extension is reduced by the impact of discounting.

The sum of the present value of net benefits in the Nash bargaining scenario (\$167.85 million) is nearly as large as the sum obtained when maximizing the sum of net benefits in the two cities (\$169.05 million). One interpretation of this result is that the Nash bargaining solution may be a desirable alternative when joint maximization of net benefits is not a viable strategy. For example, it may not be feasible for a single entity to seek the joint maximization of the sum of net benefits in El Paso and Juarez. However, there is not a large loss in potential net benefits if the two cities implement a Nash bargaining scenario.

Considering A Smaller Rate of Discount

Given the inherent value of drinking water and the potentially serious implications

of shortages in municipal water supplies, it may be inappropriate to discount future net benefits in the same way that financial returns are discounted to determine present values. City officials concerned about population growth and resource availability may place nearly equivalent values on water supplies available in the near term and in 20 years from the present. In one view, the incremental value of water resources may increase with larger populations in future, as the impacts of water shortages may be more serious and more costly at higher population densities.

We examine again the potential gains from cooperation between El Paso and Juarez using a discount rate of 1% to reflect a more even consideration of net benefits in the near term and in future. The lower discount rate does not affect the time path of withdrawals in the status quo scenario, because the two cities continue their current pumping programs regardless of marginal pumping costs. The present values of net benefits are higher, however, as those values are calculated using the lower discount rate (Table 2). The aquifer still is essentially depleted in year 18 when the pumping lift reaches 1,374 feet.

With the lower discount rate, the volumes of water remaining in year 25 increase by about 50% in the cooperative and non-cooperative scenarios. For example, in the non-cooperative scenario, the volume remaining in year 25 increases by 54% to 314,000 acre-feet. The ending volume increases by 46% to 686,000 acre-feet in the Nash bargaining scenario, and that volume is more than twice as large as the ending volume in the non-cooperative game scenario. The present value of net benefits obtained with cooperation is 2.6% higher than the value obtained in the non-cooperative game. As expected, both the relative gain in net benefits and the useful life of the groundwater reserve increase when a lower discount rate is used to evaluate the net benefits of groundwater availability in future.

Summary

The present value sum of net benefits obtained from water resources in El Paso and Ciudad Juarez can be enhanced if the cities cooperate in developing a long-term program of groundwater withdrawals. The useful life of the Hueco Bolson can be extended with cooperation and the rate of increase in pumping costs can be slowed. A slower rate of growth in pumping costs will generate economic benefits each year, while an extended useful life will provide additional time for the cities to develop alternative water sources. El Paso already has begun building a portfolio of surface water options, while Juarez is planning to obtain groundwater from an aquifer located some distance from the city. Juarez also may require surface water to meet its requirements in future, but a market for purchasing water rights from farmers is not yet available in the region.

Water demands are increasing more rapidly in Juarez than in El Paso, due to the rapidly increasing population in Juarez. Population growth is driven, in part, by migration of individuals from central and southern Mexico in search of economic opportunities in border cities. A more complete analysis of water supply and demand issues in the El Paso/Juarez region would examine optimal strategies for improving water quality and water supply reliability, while also improving the efficiency of water use and developing alternative supplies. Efforts to improve water quality and water supply are particularly important in Juarez, where the per capita consumption of water is much lower than in El Paso. The game theory framework presented in this paper may be helpful in examining the potential gains from implementing cooperative strategies for addressing several water management issues in El Paso and Juarez, including water supply and water quality. In particular, it may be helpful in examining opportunities for investing in facilities and programs that will encourage efficient use of water resources while enhancing the quality of life for residents of both cities and improving the outlook for economic growth and development in the border region.

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Table 1. Present Value of Net Benefits in Alternative Scenarios (million dollars)

Discount Rate is 5%, 25-year Scenario (Pumping ends in year 18 in status quo scenario).

	Status quo ¹	Non-cooperative Game ²	Nash Bargaining	Max Sum NB
EL Paso	9.05	25.00	25.95	22.50
Juarez	75.05	140.10	141.90	146.55
Sum	84.10	165.10	167.85	169.05
Ending Conditions				
Volume (1,000 Acre-Feet)	121	205	471	487
Pumping Lift (Feet)	1,374	1,351	1,277	1,272
Pumping Cost (\$/Acre-Foot)	131	131	123	122

¹See text for description of the status quo scenario.

²Net benefits in this scenario form the threat point for the bargaining scenario.

Table 2. Present Value of Net Benefits in Alternative Scenarios (million dollars)

Discount Rate is 1%, 25-year Scenario (Pumping ends in year 18 in status quo scenario).

	Status quo ¹	Non-cooperative Game ²	Nash Bargaining	Max Sum NB
EL Paso	8.60	36.25	38.60	29.80
Juarez	99.55	223.60	228.10	239.95
Sum	108.15	259.85	266.70	269.75
Ending Conditions				
Volume (1,000 Acre-Feet)	121	314	686	704
Pumping Lift (Feet)	1,374	1,321	1,217	1,211
Pumping Cost (\$/Acre-Foot)	131	128	116	116

¹See text for description of the status quo scenario.

²Net benefits in this scenario form the threat point for the bargaining scenario.

Figure1. Marginal Benefits and the Marginal Cost of Pumping in Year 1

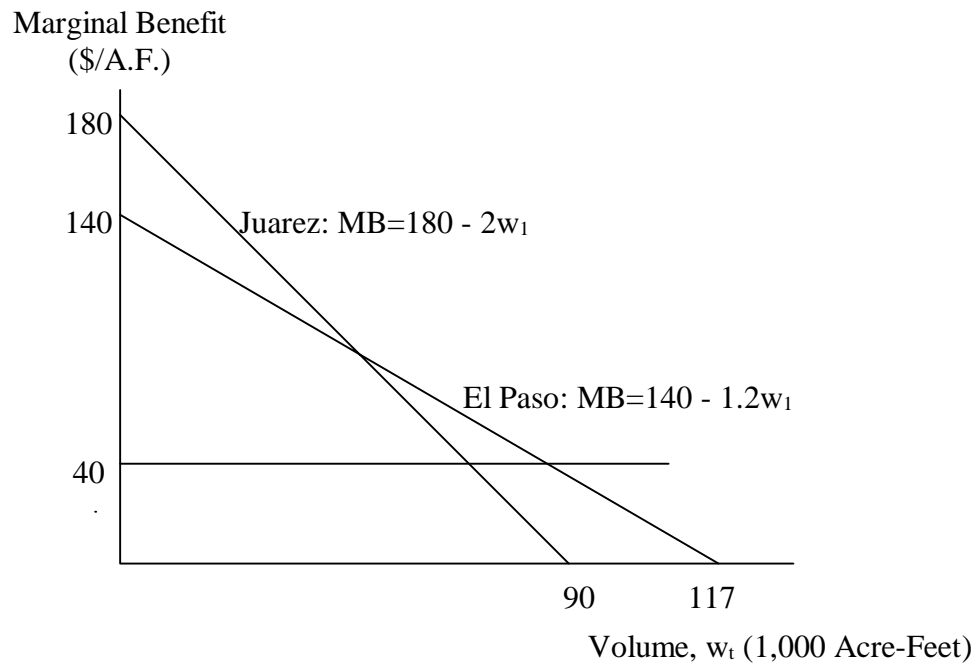


Figure 2. Groundwater Withdrawals by El Paso and Juarez in Alternative Scenarios

