Water Pollution Abatement across an International Border

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Abstract: An applied differential game theoretic model is developed to compare incentives for water pollution abatement of upstream and downstream countries under cooperative and noncooperative strategies. The Tijuana River watershed shared by the U.S. and Mexico is the empirical setting for the study. The prevailing water flow is from the south (in Mexico) to the north (in the U.S.) where the accumulation of pollution stock occurs. Asymmetry between the countries in terms of costs, damages, and emissions influence the incentives to abate wastewater pollution. This analysis investigates two North American Free Trade Agreement (NAFTA) institutions that provide financial transfers to asymmetric players in the border game. Several definitions of optimal game theoretic sharing rules (Shapley Value, Chander Tulkens rule, Helsinki Rule, Egalitarian Rule) are analyzed against actual allocations of the NAFTA institutions. In most cases of cooperation with different sharing rules, transfer payments are positive from downstream to upstream that lead to reductions in the flow and stock of pollution. The size of the transfer varies according to the rule and sensitivity analysis on changes in abatement costs and damages across the countries. The Shapley Value and Chander Tulkens Rule allocates the transfers based on economic incentives whereas the Helsinki Rule and Egalitarian Rule are based on other than economic incentives. The two NAFTA institutions presently appear to be following a variation of the Helsinki Rule.

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1. INTRODUCTION

Through half of the 20th century, international boundaries were viewed as buffers rather than centers of natural resource management. Recent growth of economic activity in cities along the U.S.-Mexico border underscores the need for transboundary environmental resource management. Natural flow in waterways traversing across more than one country's territorial boundaries generates transboundary water pollution. At the western end of the 2000 mile U.S.-Mexico border, wastewater flows with gravity from south in Mexico to the north in the U.S. in the Tijuana watershed. For the past 60 years, rapid economic development and urban population growth have outpaced environmental infrastructure in Tijuana, Mexico. Approximately 38 percent of the city is not connected to the sewer system (Guzman, 1998). Uncontained raw sewage flows into the Tijuana River, ultimately contaminating the U.S. Tijuana River National Estuarine Research Reserve and beaches in the U.S. at the river mouth.

The only infrastructure crossing the border is a wastewater interceptor from a pump station in Tijuana to the International Wastewater Treatment Plant (IWTP) in San Diego. Construction of the IWTP began in 1997 on the U.S. side of the border by agreement between the U.S. and Mexico (IBWC, Minute N. 283). Although the agreement specifies that secondary treatment will be provided at the IWTP, the first phase of this facility provides only advanced primary treatment. The IWTP receives half of Tijuana's wastewater through gravitational flow. The rest of Tijuana's renegade wastewater flows persist without adequate conveyance and treatment, partially due to financial constraints of the Tijuana State Commission for Public Services (Comision Estatal de Servicios Publicos de Tijuana, CESPT).

The proximity of San Diego to Tijuana makes them border neighbors with many asymmetries of two countries at different stages of economic development. Currently, the population in San Diego is approximately double the population of Tijuana (2850,800 to 1,299,850) (INEGI, 2003). However, the rate of growth in the population is 11.3% for San Diego and 62% for Tijuana since 2000 (INEGI, 2003). While San Diego maintains a decentralized form of governance and financial infrastructure at the municipal level, Tijuana lacks decentralized management and access to capital such as municipal bonds and municipal tax revenues. The Mexican tax system limits the taxation authority of local governments (Liverman et al., 1999).

The asymmetries between upstream Tijuana and downstream San Diego besides geography matter for transboundary environmental management. Transboundary resources such as waterways can lead to cooperation or conflict depending on the perceptions of relative benefits to each party at the boundary (Sadoff and Grey, 2002). This paper's economic analysis through applied game theory can highlight tradeoffs to the U.S. and Mexico of both noncooperation and cooperation for wastewater management in the Tijuana watershed. The upstream and downstream locations of each country are one type of asymmetry along with differences in costs, damages characterized in the model to properly assess incentives for each country's wastewater treatment strategies under both game scenarios. The asymmetries set the stage for examining a variety of sharing rules involving transfers to induce cooperation among the countries. The analysis includes quantification of the side payments under various sharing rules to solve transboundary pollution between asymmetric countries. Existing institutions through the North American Free Trade Agreement enable side payments to be made between the sovereign countries that represents diplomatic rather than litigation channels to solve the shared pollution problem. Due to Mexico’s centralized governance, transboundary management is coordinated at the federal level with NAFTA as a framework. As of 1994, two institutions, The Border Environmental Cooperation Commission (BECC) and the North American Development Bank (NADBank) have mandates to develop and finance environmental infrastructure at the border (32 I.L.M. 1545 (1993). The analysis will compare the optimal side payments through various sharing rules with the actual allocations that have been made by both the BECC and NADBank.

The following analysis moves beyond the static game framework of Frisvold and Caswell (2000) for transboundary water management and the dynamic trade and wastewater pollution work of Fernandez (2002) at the U.S.-Mexico border. The South to North unilateral pollution in the new analysis results in different asymmetries of costs, damages, and incentive to cooperate. Formal channels of financing transfers through institutions under NAFTA are incorporated into the new applied analysis. Fernandez (2005) investigates optimal strategies for solving sediment flow in surface water from south in Mexico to north in the U.S. without the formal financial funding of institutions devoted to transboundary water and wastewater projects.

Cooperation in the form of joint development water projects appears in theoretical models (Barrett, 1994, and Ambec and Sprumont, 2002). The joint development approach lends itself directly to equity analysis because a cooperative agreement between the countries must be reached regarding the decision to undertake a water project and how to distribute the benefits and costs. Jorgenson and Zaccour (2001) characterize side payments in a differential game with the egalitarian principle of dividing surplus equally rather than formally addressing asymmetry. Rogers (1997) indicates that objectives of equity and efficiency may not be met simultaneously. Some Pareto-optimal allocations can induce envy if the investment occurs only in one country (Rogers, 1997). Rogers (1997) examines the Ganges-Brahmaputra basin as an example of water allocation on an international river basin shared between India, Bangladesh and Nepal where a cooperative solution improves all countries' welfare over a noncooperative solution. Roger's static analysis involves joint optimization and compares allocations based on meeting feasibility, Pareto Admissibility and individual rationality using game concepts and engineering data of the water system.

Sadoff and Grey (2002) indicate that the redistribution of economic gains must be considered simultaneously with maximizing aggregate benefits. Cooperative game theory can accommodate such strategies involving transfers among asymmetric players for fair and efficient water allocation. Barrett (1994) analyses a static case of three riparian water countries through use of the Shapley value to select a unique, stable and efficient allocation rather than as a means to achieve equity.

The difference between the cooperative solution and the noncooperative solution depends on spillover effects of benefits and costs, which are likely asymmetric due to geographic and economic differences between the countries. Even where resource flows occur unidirectionally, precluding mutual control over negative externalities, there is the possibility of Pareto-admissable or "win-win" solutions. The upstream country imposes a negative unidirectional water burden upon the downstream country by preventing the latter from reaching an unconstrained optimal water quality. Compensation through side payments is a viable way to create incentive for cooperation. The Shapley Value, Chander

Tulkens cost sharing rule, equity, and the Helsinki rule for reasonableness are the various rules addressed in this paper for making side payments for cooperation. These rules will be compared quantitatively through the empirical case in the Tijuana watershed.
The following paragraphs describe these various rules.

The Shapley value allocates as a function of the average marginal contribution by each country to net gain from cooperation (Shapley, 1953). Chander and Tulkens (1992) indicate that transfer payments consist of two parts: a payment to cover the increase in costs between the Nash equilibrium and the cooperative optimum and a payment for each country's damage proportion according to the Chander Tulkens cost sharing rule. The Chander Tulkens cost sharing rule is similar to a Kaldor Hicks criterion.

The principle of "reasonable and equitable usage" which holds that each water user is entitled to a "fair" share of water provides a more politically feasible basis for Pareto-Admissible transboundary water sharing according to the Helsinki Rule (Beach et al, 2000). Article V of the Helsinki Rule reasonableness criteria can include: land area, hydrological share, population, and practicability of compensation as examples (Cano, 1989). A percentage of each of these physical measures in the countries considering cooperation would be the basis for sharing that accommodates asymmetry rather than simply assigning an even ratio between all countries.

In 1984 the Reagan administration imposed the equal finance rule to pay for border environmental infrastructure. Frisvold and Caswell (2000) assert that the benefit/cost ratio would have to be much higher in order for any large projects to be built under the equal finance rule. Otherwise, noncooperation would tend to be the outcome. The equal cost sharing rule was dropped in 1990, which affected an international treatment plant for the

Tijuana and San Diego region (Minute 283, IBWC, 1990). Mexico's cost under Minute 283 was assigned to equal the amount Mexico would have spent on its own treatment plant (IBWC, 1990). Minute 283 promotes individual rationality as the cost allocation for Mexico to cooperate is the same as noncooperation.

2. MODEL

The wastewater problem in this paper consists of diffuse and channeled flow across a border. The flow of wastewater is deterministic, unidirectional flow from upstream Mexico to downstream in the U.S.. Equation (1) indicates a rate of change over time in total suspended solids pollution in wastewater transported from upstream to downstream.

According to Gray and Sotir (1996), factors that influence the instantaneous rate of change in total suspended solid stock transported with and without proper piping gravitationally include the flood frequency that helps determine the volume of water in the watershed between upstream and downstream, R , the runoff flow, f , the slope length, S and abatement, A . The function combining all of the components previously mentioned is $\gamma(R, S, f)$, total suspended solids moving from the upstream portion of the watershed to the downstream portion of the watershed in the absence of abatement activities. Total suspended solid stock in the downstream (U.S.) portion of the watershed is represented by P . Reductions in total suspended solids are specified where coefficients b_1 and b_2 denote how one unit of abatement affects total suspended solids for Mexico, A_1 , and the U.S., A_2 , respectively. Thus, $b_1 A_1$ indicates abatement occurring upstream that reduces total suspended solid flow and $b_2 A_2$ refers to abatement occurring downstream that reduces total suspended solid flow. Natural decay of total suspended solids is

dP where d is a parameter $0< d <1$. Total suspended solid outflow exiting the downstream Tijuana Estuary to the sea is represented by $G(1-d)P$. Equation (1) is a measure of total suspended solids from upstream measurable at a downstream location over a period of time (Renard et al, 1997). The rate of change in total suspended solids, $\dot{P}$ in equation (1) depends on inflow minus abatement upstream and downstream minus natural decay and the component that exits the watershed to the ocean.

$$\frac{dP}{dt} = \dot{P} = \gamma(R,S,f) - b_1A_1 - b_2A_2 - dP - G(1-d)P \qquad (1)$$

Wastewater managers (CESPT) in Mexico and San Diego Wastewater Authority in the U.S. aim to minimize net cost of total suspended solids that is the sum of abatement and damages subject to the dynamics of total suspended solids. Upstream pollution damages, D_1, are a function of wastewater flow after upstream abatement, in equation (2),

$$\int_0^\infty e^{-rt}[D_1(\gamma(R,S,f) - b_1A_1) + C_1(A_1)]dt \qquad (2)$$

subject to equation (1). Upstream abatement cost is $C_1(A_1)$. Downstream, the U.S. minimizes the sum of damages and abatement costs in equation (3),

$$\int_0^\infty e^{-rt}[D_2(P) + C_2(A_2)]dt \qquad (3)$$

subject to equation (1). The cost functions in (2) and (3) are increasing, twice differentiable and convex with $C_i' > 0$ and $C_i'' > 0$. Damages are increasing in stock and twice differentiable. Game solutions will be found in terms of solving for the steady state of pollution flow, stock, and abatement. The t term is suppressed in the subsequent autonomous current value equations.

Noncooperative Game

In the Tijuana watershed, both countries minimize costs subject to the state equation. Under noncooperation, each country chooses abatement to minimize its own costs and damages with wastewater infrastructure that is physically divided into 2 portions, one for Mexico and one for the U.S. because of political boundaries, not natural boundaries.

. The noncooperative Nash equilibrium for each country acting alone can be derived through the minimization of each current value Hamiltonian of Mexico in (4) and the U.S. in (5):

$$L_1 = D_1(\gamma(R,S,f) - b_1A_1) + C_1(A_1) + \lambda_1(\gamma(R,S,f) - b_1A_1 - b_2A_2 - dP - G(1-d)P) \qquad (4)$$

$$L_2 = D_2(P) + C_2(A_2) + \lambda_2(\gamma(R,S,f) - b_1A_1 - b_2A_2 - dP - G(1-d)P) \ . \qquad (5)$$

Necessary and sufficient conditions for optimality are derived from the first order conditions, including Pontryagin's minimum principle (Kamien and Schwartz, 1991):

$$\frac{dL_1}{dA_1} = b_1 + C_1'(A_1) - \lambda b_1 = 0 \ \Rightarrow b_1 + C_1'(A_1) = \lambda b_1 \qquad (6)$$

$$\frac{dL_2}{dA_2} = C_2'(A_2) - \lambda b_2 = 0 \ \Rightarrow C_2' = \lambda b_2 \qquad (7)$$

and the current value costate equations

$$\dot{\lambda}_1 = r\lambda_1 - \frac{dL_1}{dP} = r\lambda_1 + [d + G(1-d)]\lambda_1 \qquad (8)$$

$$\dot{\lambda}_2 = r\lambda_2 - \frac{dL_2}{dP} = r\lambda_2 - E_2'(P) + [d + G(1-d)]\lambda_2$$
(9)

and the constraint equation

$$\frac{dL_i}{d\lambda_i} = \dot{P} = [\gamma(R, S, f) - b_1 A_1 - b_2 A_2 - dP - G(1-d)P]\,. \tag{10}$$

Setting equations (8)=0 and (9)=0 and solving for both shadow values, λ_1 and λ_2 yields

$$\lambda_1 = \frac{1}{r + d + G(1-d)} \tag{11}$$

$$\lambda_2 = \frac{D_2'(P)}{r + d + G(1-d)} \tag{12}$$

Through the first order necessary conditions optimal abatement is derived where marginal damages associated with higher control of sediment equal to the marginal cost of abatement. Reaction functions in (6) and (7) imply both countries control wastewater emissions where marginal costs of abatement are equal to the shadow value of damages from wastewater pollution. Equations (8) and (9) indicate the costate equations where the shadow value of wastewater equals the marginal increase in wastewater stock. Equation (9) indicates damages downstream directly impact the U.S. shadow value of wastewater. Substitution of (11) and (12) into equations (6) and (7), shows the abatement decision is related to the stock where marginal costs of abatement equal marginal damages in equations (13) and (14).

$$C_1'(A_1) = b_1\left[\frac{1}{r + d + G(1-d)} - 1\right] \tag{13}$$

$$C_2'(A_2) = b_2\left[\frac{D_2'(P)}{r + d + G(1-d)}\right] \tag{14}$$

The bracketed term on the righthand side of equation (14), has a ratio of marginal damages from deposition impacts over the instantaneous capital dividend from total suspended solid stock less the marginal rate of increase in total suspended solids transported (capital loss rate) in the watershed over time.

Each country chooses abatement that minimizes costs, taking into account asymmetry of abatement costs and shadow values of wastewater. Such minimization will be empirically compared to cooperation later in the paper.

Cooperative Game

Cooperation enables both costs and damages to be jointly minimized from the watershed scale, not at the individual country scale. The model includes the possibility of transfer payments $F(A_1, A_2)$ through NAFTA institutions of BECC and NADBank between the cooperating countries. The transfer payments compensate the loser since full cooperation does not mean each country is individually better off. Transfer payments can redistribute additional cost savings from cooperation as compensation. The current value Hamiltonian for the cooperative case is equation (15),

$$\begin{aligned} L_3 = {} & D_1(\gamma(R,S,f)+b_1A_1)+D_2(P)+C_1(A_1)+C_2(A_2)+ \\ & F(A_1,A_2)+\lambda[\gamma(R,S,f)-b_1A_1-b_2A_2-dP-G(1-d)P]. \end{aligned} \tag{15}$$

The first order conditions are

$$\frac{dL_3}{dA_1} = D_1'(-d_1)+C_1'(A_1)+F'(A_1)-\lambda b_1 = 0 \tag{16}$$

$$\frac{dL_3}{dA_2} = C_2'(A_2)+F'(A_2)-\lambda b_2 = 0 \tag{17}$$

$$\dot{\lambda} = r\lambda - \frac{dL_3}{dP} = r\lambda - D_2'(P)+\lambda d+\lambda G(1-d) \tag{18}$$

$$\frac{dL}{d\lambda} = \dot{P} = \gamma(R,S,f)-b_1A_1-b_2A_2-dP-G(1-d)P \tag{19}$$

The U.S. and Mexico must not find it in their own interest to deviate and act unilaterally. A cooperative scheme that leads to cumulative costs less than the sum of those that the countries could achieve on their own is optimal and rational (Krutilla, 1967).

Transfer payments are needed to insure that cooperation is least costly and individually rational for both countries when asymmetry is apparent.

The first order conditions can be reduced to one equation in (20),

$$\lambda = \frac{D_2'(P)}{r + d + G(1-d)} \tag{20}$$

In equations (20) the sum of damages is taken into account in the shadow value of total suspended solids that differs from the noncooperative case. As damages increase, abatement increases in order to avoid the damages. Substituting (20) into (16) and (17), shows marginal costs equal marginal damages in equations (21) and (22).

$$(21)\ D_1'(-d_1) + C_1'(A_1) + F'(A_1) = b_1\left[\frac{D_2'(P)}{r + d + G(1-d)}\right]$$

$$(22)\ C_2'(A_2) + F'(A_2) = b_2\left[\frac{D_2'(P)}{r + d + G(1-d)}\right]$$

Asymmetry between the U.S. and Mexico determines the size of transfer payments $F'(A_1)$ and $F'(A_2)$. The country with lower net costs of wastewater abatement and higher transboundary environmental benefits under cooperation could make pay the transfer. Thus, the transfer will meet individual rationality if overall costs are minimized more with the transfer under cooperation, than costs in a noncooperative game.

If $C_2' + D_2' > C_1' + D_1'$, country 2 is willing to pay country 1 for increasing its level of abatement in order to avoid larger costs. If country 1 has a lower cost of abatement, it may take over the obligation to reduce emissions from the other country that has the higher marginal abatement costs and can receive compensation for its additional costs.

In downstream country 2, the transfer can foster pollution load reduction and total environmental damage reduction. In this specific case, country 2 has a duel incentive to pay country 1; lower costs as well as higher benefits. It will be possible to explore empirically the variation in sharing rules and transfers when cost and damage asymmetries are quantified. The relative magnitude of each will help determine division of the cooperative savings. The site of the cooperative savings matters in order to make transfer payments between cooperators.

3. DATA

The state equation of water quality dynamics draws on numerical measures of water flow, slope and flood frequency from the Southwest Wetlands Interpretive Association (1999), Gersberg et al. (2000) and Fong and Zedler (2000). The referenced value for f is in cubic feet per year from Fong and Zedler (2000) based on average rate over four years and values of $R=0.34$ and $S=0.83$ are in % units according to Southwest Wetlands Interpretive Association (1999) and Gersberg et al. (2000). The functional form set by the advection diffusion total suspended solids equation is fRS from upstream to downstream. Average water flow over several years yields a reference value of $f=58$ (Southwest Wetlands Interpretive Association, 1999; Zedler, 1998). Estimates for b_1 and b_2 are based on the wastewater abatement in removing micrograms per liter (mg/l). For Mexico, $b_1=0.69$ and for the U.S., $b_2=0.71$ (CH2MHill, 1997, 1998)

Abatement in Mexico consists of various projects to install sewer connections and wastewater treatment described below that contributes to estimation of an abatement cost function. Abatement includes labor and equipment costs of constructing infrastructure per year. Tijuana's wastewater conveyance system prior to 2004 had a nominal capacity of 35 MGD through a lift station and an open channel has been incomplete. The 2004 sewer installation increased conveyance capacity to 50 MGD. For the number of household connections through 2005, there are 340 miles of sewer pipes, 15 miles of collectors and plant upgrades to build into the estimation.

Tijuana's conventional wastewater treatment plant since 1989, San Antonio de los Buenos, needs expansion and rehabilitation to help address wastewater for part of the city with more than the current primary wastewater treatment for 17 MGD. The inflow levels of TSS are 211 mg/l and the effluent is approximately 70 mg/l (DHTA, 1996).

As a complement to conventional wastewater treatment, Ecoparque treats inflows from Otay Universidad housing area in Tijuana up to 273,600 gallons per day. Ecoparque is biofiltration with preliminary treatment of a settling basin at the inflow desilting channel to separate objects that obstruct treatment, primary treatment used to control odors and increase dissolved oxygen and secondary treatment with biofiltering vegetative media to remove dissolved organic matter and collect sludge as well as disinfect the waste flow (COLEF, 1997).

The Tijuana Water Master Plan compiled in 2000 is part of the engineering and planning realm of infrastructure costs with an expenditure of $2 million (BECC, 2003).

Parameters in Mexico's wastewater abatement cost function result from regressing both operating and capital costs measured in U.S. dollars on the quadratic form of TSS in mg/l. The fixed costs are combined with variable costs since they are annualized using a rate of 5% over a twenty-year interval for the projects discussed above. Mexico's cost function appears in equation (23) with standard errors in parenthesis below.

$$C(A_1) = 0.66 + \underset{(0.76)}{3.79A_1} + \underset{(0.008)}{0.038A_1^2}, \quad R^2=0.70 \tag{23}$$

U.S. abatement expenditures of the projects discussed in the following paragraphs cover capital cost for equipment and operating costs of labor in a similar manner as described for Mexico with annualized fixed costs.

Before the IWTP was built, inflows exceeding 211 mg/l routinely bypassed the treatment plant and were combined with treated effluent prior to discharge into the Pacific Ocean without an outfall that would provide the dilution in deep water.

The South Bay Water Reclamation Plant is adjacent to the IWTP, to be part of the City of San Diego water reclamation system to provide 15MGD of tertiary treated effluent. Such effluent complies with Title 22 of the California Code of Regulations, making it suitable for unrestricted landscape irrigation. The cost is $99,588,000 with $42 million covered by U.S. EPA (San Diego Wastewater Authority, 1997). Plant effluent not used for irrigation or other purposes is discharged through the S. Bay Ocean Outfall. The plant capacity was expanded from 7.5 MGD to 15 MGD during construction with the expectation of selling the additional flow of recycled water to Mexico. The potential market has not been quantified yet. Additional issues have not been resolved, such as a binational agreement to transfer the water, the cost of purchasing the recycled water and the social issue of exporting U.S. wastewater.

CH2M Hill (1997, 1998) conducted a study of 2 options to upgrade the IWTP to secondary treatment, activated sludge and advance pond system with the following costs. Activated sludge has $70,800,000 in capital costs, $5,300,000 in operation and maintenance costs with a present value of $206,200,000 for a 40 year plant life. Advanced pond system has $21,600,000 in capital costs, $2,900,000 in operation and maintenance costs with a present value of $93,900,000 including the $550,000 cost of land. The pond system was selected and has yet to be implemented.

Wastewater treatment costs for the U.S. are according to equation (24),

$$C(A_2) = 2.6 + 3.9A_2 + 0.057{A_2}^2 \qquad (24)$$

$$(0.84) \quad (0.009), \quad R^2=0.71$$

with standard errors in parenthesis.

Damages are a function of the quadratic stock of pollution, $D_2(P^2)$ where D_2 is an index of impact of TSS stock for the U.S. health problems of exposed populations. With the buildup of TSS there are harmful pathogens that exceed the California state regulation limit for health and environmental degradation (Cabelli et al, 1983). The U.S. damage function is based on benefits transfer of values generated with the cost of illness technique that includes lost revenue and medical expenses for people impacted by gastrointestinal illnesses (Dwight et al, 2005) that has been applied to 28 beaches spanning 160 kilometers of coastline in Southern California (Given et al, 2006). Such morbidity impacts are from exposure at beaches downstream at the mouth of the Tijuana Estuary. The number of exposures multiplied by the illness rate yields the number of illnesses that are valued through benefits transfer. The population at risk was estimated using data on beach attendance provided through local lifeguard agencies and reports on the proportion of beachgoers who bathe seasonally (SANDAG, 2003). The medical expenses are calculated from the proportion of exposed people requiring medical help multiplied by the average cost of medical care (Dwight et al, 2005). The TSS correlation to illness dose was referenced from Cabelli et al. (1983). The monetary values do not include lost recreational values or the willingness to pay to avoid getting sick from swimming. Equation (25) indicates downstream damages.

$$D_2(P) = 29.76P^2 \tag{25}$$

Mexico's damage function is based on estimates from the Mexican Association of Insurance Institutions (Vargas Aguilar, 2003) related to lost property value as a function of quadratic diffuse wastewater flow that destabilizes eroding land underlying colonia residences. Colonias are residential subdivisions in unicorporated areas. They lack basic services of drainage, paved roads and public utilities of electricity, water and wastewater treatment (Pombo, 1998). The value of damages in Mexico is expressed in equation (26) as follows:

$$D_1(P) = 18.47\,(\gamma(R, L, f) - b_1 A_1) \tag{26}$$

The F parameter of the transfer payment function is derived from the range of grants for wastewater projects that have been discussed in the previous paragraphs, as a function of wastewater flows that these projects address. Since 1994, the U.S. has appropriated $575 million to the U.S. Environmental Protection Agency (EPA) to reduce public health and environmental risks on both sides of the border. EPA supplements binational funding for the projects discussed in previous paragraphs formally channelled from the Border Environmental Cooperation Commission (BECC) and the North American Development Bank (NADBank). EPA's money helps capitalize BECC's technical assistance (PDAP) program and provides grants through the Border Environmental Infrastructure Funds (BEIF) of the NADBank [(BECC, 2003); (NADBank, 1998)]. The U.S. General Accounting Office recognizes that EPA funding has been critical for completing environmental infrastructure projects along the U.S.-Mexico border (U.S. GAO, 2000).

Within the Tijuana River watershed, BEIF grant funds from the U.S. EPA channeled through NADBank cover 88% of the $19.52 million cost of a conventional wastewater treatment plant in Tijuana, San Antonio de los Buenos, and 43% of the $30 million cost of improving Tijuana's sewer lines. Ecoparque, has transfer payments in the form of 80% of the $180,000 total costs covered by grants from NADBank with EPA funds.

The interest rate for the analysis is 5% with all values adjusted to 1998 dollars as the base year (Federal Reserve System, 1999).

4. RESULTS

Maple software is used to compute the constrained optimization game solutions with steady state sediment stock, abated flow, cost savings, and the amount of transfer payment for the two countries. The results correspond to the case where marginal costs of abatement and damages increase from upstream to downstream. Table 1 presents the steady state results for all game scenarios. Rows 4 and 5 for noncooperation and rows 7-10 for cooperation constitute the baseline case. The steady state stock declines by 19.4% with cooperation compared to the noncooperative game shown in Column 2. Aggregate cost savings of $1,316,865 for both the U.S. and Mexico are attributed to the cooperative solution. Subtracting the optimal cooperation minimized cost from the noncooperation cost yields the cost savings recorded in Table 1. Due to the strong link of upstream abatement influencing downstream benefits, the U.S. saves costs of $888,676 and abates 2.5% more with cooperation than without. The avoided costs of the U.S. are better with the unilateral financial transfer since Mexico increases its abatement. Upstream under cooperation cost savings of $428,189 accrue due to lower damages from increasing abatement by 16% over the noncooperation case.

The less optimal noncooperative case mirrors what has resulted from the meager attempts by the Tijuana State Commission for Public Services (Comision Estatal de Servicios Publicos de Tijuana or CESPT) to unilaterally build a system that fights gravity by constructing pipelines, a pump station and a canal to keep water at a high elevation and redirect the flow to a treatment plant to the west. Because of the incomplete system with construction deficiencies, deferred maintenance on the conveyance structures and overwhelming cost of continuous operation of the pump station, raw wastewater flows persist across the border.

A sensitivity analysis for the size of the transfer is conducted through different types of sharing transfer payments. All types follow the property of additivity as cost shares in percentage units in columns 5-10 of Table 1 sum to one for Mexico and the U.S.. The types can be compared on the basis of properties such as individual rationality, group rationality, and Pareto optimality and size. All three properties are met with the Shapley value and the Chander Tulkens cost sharing rule. However, none of the properties are met with the equity rule (Folmer et al, 1998). The three properties may not be met by the Helsinki rule of reasonableness. Differences among different types of sharing transfer payments are presented below.

Three criteria of population, land area and hydrology are part of the Helsinki rule of reasonableness appearing in column 5 and rows 8 and 9. Approximately 34% of the cost savings should be earned by Mexico and 66% by the U.S. if the criterion is size of the population. These percentages are based Tijuana’s population of 1.2 million and San

Diego’s of 2 million (INEGI, 2000; U.S. Census Bureau, 2000). Adjusting the initial cost savings allocation from $428,189 to increase by $19,545 dictates the transfer to Mexico since the total will be 34% of $1,316,865. With land area and water of the watershed are the criteria, the shares and transfers are based on 90% physical shares of both natural resources located in Mexico. For Mexico, 90% of $1,316,865 would be reached by transferring $756,989 from the U.S. to Mexico.

With the Shapley value type of sharing the upstream country receives a payment in proportion to its contribution to the cooperative cost savings. Thus, the transfer payment is based on Mexico’s increase in abatement. Numerically, Mexico contributes 43% of the cost savings and the U.S.’s contribution is 57%. The Shapley 43% share of $1,316,865 aggregated cost savings is based on a transfer of $138,063 to Mexico.

With Chander/Tulkens cost sharing rule that makes Mexico as well off as without cooperation, the cost savings to Mexico is positive without the transfer for all cases. Allocation of cost savings according to the change in costs (not damages) from noncooperation to cooperation also leads to a transfer payment Mexico. A transfer of $59,051 as compensation is based on Mexico’s increase in abatement costs by 37% of the cost savings. Where noncooperation yields less abatement costs from less abatement, the damages are higher as a function of the higher sediment stock in column 2.

The equity sharing rule is assessed in the last column. This rule is less applicable as it was formally removed from U.S.-Mexico policy in 1990 through IBWC Minute 283.

In rows 12-15, the results of a 20% increase in costs is shown for both countries. In rows 17-20, the results of a 30% increase in damages is presented.

For the scenario of cooperation yields costs increase by 20%, the aggregate cost savings of $329,600. Mexico has a 4% increase over the noncooperative case compared to the baseline case. The U.S. increases abatement by 4.7% to avoid higher damages if Mexico's abatement does not increase. Columns 5-10 and rows 13-15 indicate transfer payments based on the reasonableness criteria. With the population criterion, the transfer payment is $4,806 and if hydrological share or land area are criteria, the transfer increases to $189,382. With the Shapley value, the U.S. makes a larger marginal contribution to the joint cost savings. Hence, 60% would be allocated to the U.S., while Mexico's share is 40%. The transfer of $24,582 decreases in size compared to the baseline and the reasonableness criteria. The Chander Tulkens cost sharing rule leads to a transfer of $27,878.

The case of 30% in damages results in cost savings from cooperation of $2,687,222. Both countries increased their abatement to avoid larger damages. The stock decreases as a result. A 46% decrease with cooperation versus noncooperation is shown in column 2 and the last row. Increases in abatement are based on cost savings from avoided damages.

Mexico needs less of a transfer to induce abatement in order to avoid the higher damages in the case of the population criterion that awards more cost savings to the U.S. In fact, $40,397 is presented in parentheses in column 5 and the last row of Table 1 because it is the amount Mexico should transfer to the U.S. due to the share of 66% due to the population criterion. Aside from this case of a high share for the U.S., all other allocation methods for all other scenarios require a positive transfer payment from the U.S. to Mexico. The transfer payment is $1,545,742 when land area and hydrology are the criteria for reasonableness. With the Shapley value, Mexico’s marginal contribution is 44% from the larger abatement increase of 53% over the noncooperative game. Then the transfer payment to Mexico is $309,120. The transfer is $13,525 with the Chander Tulkens cost sharing rule.

5. CONCLUSIONS

Transboundary wastewater pollution is addressed in this comparative study of game solutions. Data from the U.S.-Mexico border is accessed for quantitative analysis. Asymmetry in budgets, abatement costs, and damages between upstream Mexico and downstream U.S. are included in the empirical analysis. Incentives for controlling wastewater pollution consist of preventing loss of property upstream and protecting public and environmental health downstream.

Results show that coordinated binational abatement involving transfer payments from downstream to upstream is optimal for minimized costs, damages, and stock of wastewater pollution. Mexico’s location and lower marginal cost advantage make it economical to pay for abatement upstream and avoid more severe damages. The negative externalities from wastewater are internalized by analyzing the watershed as a binational single unit through cooperation. Mexico gains less than the U.S. from cooperation for the baseline case. This is due to lower marginal damage costs than downstream in the U.S.. Abatement will be attractive to upstream Tijuana if there is incentive to avoid damages. Upstream abatement increases the likelihood of success for reduction in pollution in the watershed. Transfer payments to Mexico enable control at the source of pollution and hence drive down the stock. The transboundary pollution impedes the downstream U.S.

estuary as well as possible damages upstream. Thus investment upstream is essential. For Mexico to cooperate, the compensation varies according to different types of sharing for all cases.

If transboundary cooperation for infrastructure had been envisioned when the original wastewater infrastructure was conceived, it is possible that more reliable and less costly infrastructure could have been constructed as shown by the difference between the noncooperative and cooperative cases in the baseline analysis. A pipeline crossing the border and paralleling the river, a treatment plant at low elevation in the U.S. and discharge of treated effluent through an ocean outfall like those typically used in the U.S. would have resulted through the cooperative solution. By 1998, at least the IWTP and S. Bay Ocean Outfall in the U.S. work with gravity to treat and discharge about half of Tijuana's wastewater in a cooperative way.

The Shapley value, the Chander Tulkens rule, and the Helsinki Rule of reasonable and equitable sharing are among the allocation rules in the study. While the population criterion for reasonableness to allocate shares of costs savings indicates a minor amount for transfer payment in all cases, this method is questionable as population may mean growth inducing activities would dictate more financial incentives for impacting water quality negatively. Permanent characteristics of land and hydrology imply the upstream has a higher share corresponding to the 90% amount Mexico holds in the watershed. Transfers could increase dramatically with both characteristics as criteria.

Transfer payments from downstream to upstream are large in the baseline case with the Chander/Tulkens cost sharing rule and the Shapley value. The TSS stock is lowest with both sharing rules.

Asymmetry in financial resources between upstream and downstream makes transfer payments imperative. Tijuana's municipal budget is a proportion (0.05) of San Diego's budget [(INEGI, 2003); (SANDAG, 2003)]. All municipalities in Mexico including Tijuana receive only 4% of the annual federal budget, the only source besides the binational institutions for funding public works (Zepeda, 1993).

A policy change in 1990 referred to as IBWC 1990 Minute 283 accommodates asymmetry between countries through allocation of cost savings other than the equity rule. This policy change is validated through this study that indicate all results other than equity address asymmetry. Prior to 1990, an equal cost share rule on jointly developed pollution control projects impeded efficient solutions to the border sanitation problems in the San Diego-Tijuana region (Mumme, 1993).

One criterion of the Helsinki Rule is used by NAFTA institutions for allocation in the Tijuana River watershed as well as the rest of the U.S.-Mexico border. The BECC and NADBank include population as a criterion for projects they approve and fund.

The current amount of finances and technical assistance devoted to Tijuana for helping control upstream wastewater is lower than it should be in all cases as shown in the difference between transfers using the Helsinki rule with the population criterion versus any other sharing rule included in this analysis. Transfer payments to Mexico could be higher to abate wastewater. Institutions pondering water quality improvement projects can use the results of this study to determine funding allocation for the right mix of incentives upstream and downstream.

As more wastewater treatment is considered (secondary treatment) the size of the transfer payment can be an integral part of implementing the infrastructure on either side of the border. Under the terms of IBWC Minute No. 283, Mexico is entitled to the treated effluent from IWTP (in the U.S.) for the uses it deems appropriate; thus, provisions have been made in the plant's effluent structure to connect to a future pump station and pipeline that would return the flow to Tijuana should Mexico request it. However, until additional treatment is provided, the toxicity of the effluent may deter recycling efforts.

A current proposal from the private sector to build secondary treatment in Mexico is referred to as Bajagua provides a context to explore the extent of U.S. interest in financing upstream wastewater treatment. A pump station, conveyance pipeline, and return pipeline to allow discharge of excess effluent through the S. Bay Ocean Outfall if reuse does not consume all of the effluent is envisioned for Bajagua. This proposal prompted the U.S. Congress to pass legislation (Public Law 106-457) to provide a revenue stream to pay for construction, operation, and maintenance of a secondary treatment plant in Mexico.

To implement this type of project, IBWC Minute No. 283 would have to be amended since the original document stipulates that all treatment is to be provided in the U.S. Both countries have agreed to negotiate to amend Minute No. 283. This plan has been developed as the IBWC has delayed making a decision on secondary treatment alternatives for the IWTP past its 1999 deadline for a permit in order to have the option of ponds in Mexico.

The model is deterministic from actual data on the Tijuana watershed. The model and results from the analysis are useful to other efforts worldwide given the amount of these watersheds and the increasing number of conflicts in need of a formal method to solve transboundary problems.

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Table 1 Steady State Values of Stock, Abated Flow, Cost Savings, Percentage Shares, and Transfer Payments

				Allocations (% units for each country's share)					
Game Scenario	Stock	Abated Flow	Cost Savings	Prop. Pop.	Prop. Area	Prop. Hydrol.	Shapley	Chander Tulkens	Equity
Baseline	(cubic ft.)	(cubic ft.)	(U.S.$)						
Noncoop.U.S.	34.20	11.60							
Noncoop. U.S.		18.54							
Cooperation	% units <noncoop.	%units >noncoop.							
U.S.	16.6	2	808,661	66	10	10	20	25	50
Mexico		14	386,551	34	90	90	80	75	50
Transfer (U.S. $)			1,195,212	19,821	689,139	689,139	569,618	509,858	211,055
Cost Increase									
U.S.	5.4	8.2	268,303	66	10	10	54	43	50
Mexico		7.1	133,231	34	90	90	46	57	50
Transfer (U.S. $)			401,534	3,291	228,149	228,149	51,474	95,643	67,536
Damage Increase									
U.S.	48	26	1,719,531	66	10	10	42	62	50
Mexico		36.3	938,901	34	90	90	58	38	50
Transfer($U.S.)			2,658,432	(35,034)	1,453,687	1,453,687	602,989	71,303	390,315