Hydro-economic modeling of the benefits and costs of water management in the Santa Cruz border region

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Abstract: Water management along the transboundary Santa Cruz River basin overlapping Arizona and Mexico, faces a host of physical, economic and institutional challenges. The situation is worsened by a failure of bilateral strategies to achieve an administratively feasible solution to these problems, given different layers of governance regulating water use in each country. The current study, utilizing data from the Santa Cruz Active Management Area in Arizona and the city of Nogales in Mexico, takes an integrated approach towards water management along this region, accounting for the physical, economic and institutional constraints in water management and allocation. The baseline optimization model suggests higher optimal water use and higher net benefits from water use in the residential sector on both sides of the border, while agricultural sector overall shows the lowest net returns from water use. Results from a scenario where population growth is combined with water shortages, suggest redistribution of water use within the nonagricultural sectors in each region, with a marked impact upon residential water use benefits on the Arizona side.

Keywords: *Transboundary, integrated approach, net benefits, sectoral water use, US-Mexico*

JEL codes: Q2, Q5

1. Introduction and Background

Transboundary water management along the US-Mexico border has gained a prominent place in recent years due to burgeoning population in border cities, rapid growth in economic activities and mostly unfavorable climatic patterns. Some of the worst ramifications of climate variability include low precipitation, streamflow variability, abrupt changes in the timing of snowpack melt and severe droughts in several parts of California, Arizona, Colorado and Texas as well as in Mexico´s Border States such as Baja California, Sonora, Chihuahua, Coahuila, Nuevo León, and Tamaulipas. The resulting high demand for water has inevitably made it a scarce resource in terms of quantity and often in terms of quality, as proper infrastructure for treating effluents are often nonexistent in these regions. Yet, one fundamental problem that pervades water management along the border has been the failure of binational strategies to arrive at a consensus on water related issues, in some of the most affected regions of the border.

The Santa Cruz River Basin along Arizona is a case in point. The basin covering 716 square miles of the Santa Cruz River valley along the border, originates in Arizona, flows south and the turns north towards the Mexican border through Nogales, Sonora, and crosses back to the U.S., flowing north until it meets the Gila River. Interconnected with the basin is the Santa Cruz aquifer, which is the main source of water for communities in the Santa Cruz County in Arizona (the most important being the City of Nogales) and also for Nogales, Sonora.

Both the cities of Nogales AZ and Nogales, Sonora have witnessed rapidly growing populations. The population of Nogales- Sonora increased by 50% during the 1990s and between 2000 and 2020, its population is expected to increase by 86%. Nogales AZ, on the other hand, has a population of less than 25 thousand but during the 2000-2020 period it is expected to grow by 67% (Ingram and White, 1993, Frisvold and Caswell, 2000). In fact, rapid growth in population and almost complete dependence upon the aquifer by the two cities have left wells, drawing water from the Santa Cruz aquifer, severely depleted in many cases (ADWR, 2007, 2012). Both regions have inadequate water storage capacities and the high population tends to put more stress on water resources and infrastructure. This has led to vulnerability to water shortages during droughts particularly for Nogales, Sonora (Ingram and White, 1993). On the other hand, low and highly variable surface water flows have affected the amount of recharge to the aquifer as well as the maintenance of the riparian ecosystem in the upper Santa Cruz basin in Arizona.

Though two water treatment plants are currently in place in both US and Mexico, the flow of wastewater from Nogales, Sonora to the predominantly US sponsored Nogales International Wastewater Treatment Plant (NIWTP) and the subsequent use of the treated water, constitutes another bone of contention in this border region. The establishment of the second treatment plant in the Los Alisos Basin south of Sonora, Mexico is essentially a fallout of this contention, with Mexico deciding to conserve a part of its effluent and thus reducing the cost it has to bear for effluent treatment in the United States (Prichard and Scott, 2013). A portion of the wastewater from Nogales, Sonora now flows into the Los Alisos Water Treatment Plant (LAWTP) instead of being diverted for treatment entirely to NIWTP. Also, treated water from the LAWTP is meant to recharge the Los Alisos aquifer from where Nogales, Sonora draws a portion (26%) of its water supply. This has potentially reduced the amount of wastewater being directed to the NIWTP on the US side, where release of treated wastewater constitutes a source of instream flows for supporting and restoring the riparian vegetation.

As is evident from the discussions above, water management along the Santa Cruz River Basin is fraught with a milieu of physical, economic and institutional challenges, not very different from the complexities of border water management seen in the Lower Rio Grande Basin or the Baja California region. What makes the Santa Cruz case unique, however, is the evolution of the problems over time that has affected some of the largest growing cities along the border, with water from the aquifer serving not only a large municipal population but some booming industrial activities, as embodied by the maquiladoras on the Mexican side. A wide range of studies have identified the interconnected problems of increasing population, rising water demand and the depleting Santa Cruz aquifer and have advocated better coordination in bilateral water management (Frisvold and Caswell (2000); Fernandez (2013); Varady et al. (2013)). In addition, a long standing debate, (spearheaded primarily by members of the International Boundary and Water Commission (IBWC)) has continued, on how to achieve an administratively feasible solution to these problems given different layers of governance involved in regulating water use in each country. However, there remains a lack of insight on how the problems may be interconnected across space, using an integrated approach that takes into account the physical, economic and institutional constraints in water management and allocation.

Our main objective is to highlight and assess some of the economic consequences of these challenges facing water allocation across the two border cities, under such existing constraints. To this end, we first develop an integrated (hydroeconomic) optimization model of water use across the three major sectors — agriculture, residential and non-residential (industrial and commercial) — for the Santa Cruz border region. This "baseline" model provides a holistic assessment of the economic costs and benefits of water allocation, instrumental in driving future water management in this transboundary peri-urban region. Second, we attempt to determine how population growth, drought- related water shortages, and use of treated or reclaimed wastewater influence water demand, availability and the economic benefits and costs of water allocation for both regions along the border. These "scenarios" are designed to compare the relative outcomes in terms of water demand, optimal benefits and opportunity costs of water use in each sector, under the baseline and under the different scenarios.

In the following section, we provide a brief overview of existing literature on water management in transboundary regions and delineate some of the salient contributions of the present study. In Section 3, a conceptual model for integrated water management is laid out where water is shown to have competing demands across sectors. In Section 4, we highlight specific characteristics of the study region and data sources. Section 5 outlines the results from the baseline model and the scenarios considered and discusses some sensitivity analysis of the main parameters. Section 6 briefly touches upon some equity implications. We conclude in Section 7, outlining some limitations of the study and scope for further extensions..

2. Literature review

Several studies over the past three decades have emphasized the importance of management of transboundary shared water resources. These studies may be grouped into two separate strands of literature. The most common among these strands has been studies upholding bilateral or multilateral negotiations in water management among states and amongst countries (Frisvold and Caswell, 2000; Baker and Willis, 2006; Dinar et al., 2013; Chowdhury and Islam, 2015). While there exist multifarious compact agreements for sharing surface water —for instance the Rio Grande Basin overlapping US and Mexico or the Amu Darya Basin covering Central Asian republics—managing groundwater across borders has often eluded the attention of policymakers. Part of the reason of course, is the common pool nature of groundwater resource as well as complexities arising when surface water and groundwater are hydraulically connected, which makes administrative rules difficult to implement (ADWR, 2012).

The physical and economic challenges of managing water across borders for the Santa Cruz Basin where groundwater constitutes the primary source of water, are thus enormous. As explained in Milman and Scott (2010) and Megdal and Scott (2011), one missing link is the coordination or the lack of institutional consensus between the two countries, given disparities in problems faced and information asymmetries. Frisvold and Caswell (2000) approach the US-Mexico transboundary water problem as a typical Nash bargaining game, suggesting that technical support, assistance, water rights and regulations all affect the outcomes of the negotiations. Along similar lines, Fernandez (2013), employing three game theoretic scenarios for polluted wastewater reduction in the US-Mexico border, demonstrates that a Stackelberg solution leads to cheaper costs of pollution abatement in Mexico than domestic measures.

Over the last few decades, economists have recognized climate variability problems as embodied by droughts and water scarcity problems, as one major source of transboundary water conflicts. Thus, several studies have identified the costs and benefits of water allocation at a basin scale, when water may be considered a scarce commodity affected by physical, economic and institutional factors (Booker and Young, 1994; Booker, 1995; Booker et al., 2005; Ward et al., 2006; Maneta et al., 2009; Harou et al., 2010; Ward and Velazquez, 2012). Most of these studies conclude that an integrated water management approach is ideal in such situations, since it can specify both spatial and temporal policy goals in terms of such factors (Ward et al., 2006).

Though the applicability of this approach have shown success in the United States and elsewhere, in cases like the Santa Cruz Basin, it is yet to be explored. While climate variability is an issue in this region, most studies have conducted simulation based water demand and supply analysis considering projected growth rates in population along this border (ADWR, 2012; Scott et al., 2012; Norman et al., 2013; Shamir et al., 2015). As a result, optimal and efficient allocation of water use and resultant benefits and costs of allocation across sectors and regions are not given required importance. This is relevant mainly because of the negotiations and project developments that have taken place in recent years in order to solve water quantity and quality problems. Also, as pointed out in Wilchens (2001) and Nakao et al. (2002), water management and adaptation is one of the most important mechanisms to make border regions viable and sustainable in the medium and long run. The present study fills in this gap by utilizing an integrated approach that includes some of the institutional constraints or regulations on water use in major sectors. In addition, the study, by presenting outcomes from different scenarios like water shortages and population growth, underscores the need for integrating economics with simulation based studies, addressing water demand and supply gap, such that better policy directions may be achieved in the future.

3. Model and Methodology

An integrated water resource management framework may be interpreted as a joint maximization of net economic benefits, within a spatially differentiated river basin model (Booker and Young, 1994; Booker, 1995; Ward and Velazquez, 2012), so as to achieve an economically efficient allocation of water across all uses. The objective is to maximize net benefits from water use, subject to relevant constraints upon water availability and various institutional mechanisms guiding water use in each region of the study area. An integrated water management approach is utilized for our current study due to the following reasons. First, a wide range of studies for this region have identified the interconnected problems of increasing population, rising water demand and the depleting Santa Cruz aquifer and have advocated better coordination in bilateral water management. As previously mentioned, notable studies by Frisvold and Caswell (2000), Varady et al. (2013), Fernandez (2013), Bark et al. (2014) have provided economic solutions through Coasian bargaining and strategic game theoretic models, but there remains a lack of an integrated approach that includes both institutional and economic constraints in water management. Thus, they have failed to lend further insights on the effect of institutional changes upon the economic benefits and costs of water allocation. Second, an assessment of the net benefits across the major water users in the region, along with the allocative and distributional impacts of water shortages driven by high population and growth in economic activities in the peri-urban region, has two major implications. One, it incorporates optimal allocation of water use within sectors based upon population served in the border region, including the twin cities of Nogales, where the sectoral water demand has shown diverse growth in recent years. Two, by including both physical and institutional constraints, it provides an estimate of the opportunity cost of water allocation for different water management policy scenarios, within and across sectors in the region.

Sectoral net benefits from water use

The determination of optimal net benefits from competing demands for water follows the approach taken in Ward et al. (2006), Maneta et al. (2009), Howitt et al. (2012); Booker and Young (1994,1995) and many others who have applied basin scale spatial optimization techniques to assess the relative benefits and costs of water allocation. In Mexico an example of this type of study is Soria et al. (2006). These methods can be applied at a smaller regional level, as is done in the current paper. Maximization of the aggregate benefits or the economic surpluses obtained from water use across all sectors given relevant physical, economic and institutional constraints, provides optimal levels of water use in each sector, the economic returns from water use and the opportunity costs of water allocation within and across sectors in the region.

3.1.1: Net benefits from water use in the agricultural sector

A deductive method of determining net returns to irrigation water, through varying input constraints or water prices in a linear programming framework is often adopted to evaluate agricultural water demand in the absence of actual data for estimation of an agricultural demand function. As noted by Booker et al. (2012), a major limitation of this method is the ex-ante assignment costs of pre-owned inputs into the model (Booker et al., 2012), for which Howitt (1995) offered an improvement by the introduction of the positive mathematical programming (PMP) procedure. The PMP methodology essentially allows greater flexibility than the linear constraints by inserting a nonlinear yield or cost function for the production activities. It employs observed values for crop acreage and input and output parameters from the base year to generate self-calibrating models of agricultural production and resource use, consistent with microeconomic theory and accommodating variations in land quality, risk behavior and rotational constraints. (Howitt, 1995). For determining net benefits in the agricultural sector, we apply a simplified version of the PMP method as used in studies by Gohar and Ward (2010); Dagnino and Ward (2012); and Gohar et al. (2013). (For details, refer to Appendix A in the Appendix section).

We assume that agricultural producers maximize net economic returns to irrigation water subject to regional level (institutional) constraints on total agricultural water withdrawal. Let the subscript r represent the region for our study area. (If r is 1, the region is Sonora in Mexico and r equals 2 the region is Arizona (SCAMA)). Producers' profits π_{rA} or net returns from water use as a function of the amount of land devoted to agriculture takes the following form

$$\pi_{rA} = \sum_{k=1}^{K} [P_{rk} y_{rk}(L_{rk}) - C_{rk}] L_{rk} - C_{rw} \qquad (1)$$
$$(r = 1,2)$$

where P_{rk} denotes the region specific crop price, $y_{rk} = f_{rk}(L_{rk})$ represents region specific crop yield, C_{rk} and C_{rw} represent region specific non-irrigation costs of crop production and pumping costs respectively, and L_{rk} is the amount of irrigated land devoted to crop k in region r. The model makes the simplified assumption that that agricultural activity takes place at the regional level r, something that will be relaxed for water use benefits in the non-agricultural sectors.

A balance constraint for all irrigation water used for agriculture in region r is represented as follows:

$$\sum_{k=1}^{K} w_{rAk} L_{rk} = W_{Ar} \qquad (2)$$
$$(r = 1,2)$$

where w_{rAk} is the amount of water applied for production of crop k in region r and The variable W_{Ar} represents the total amount of irrigation water used in region r.

Agricultural water use in each region is constrained by the level of permitted water withdrawal as shown by the following constraint:

$$\sum_{k=1}^{K} w_{r,k,A} \leq \overline{W}_{Ar} \qquad (3)$$

where, $\overline{W}_{Ar}$ represents the maximum level of water withdrawal permitted in that region. By the assumptions inherent in our PMP methodology, w_{rkA} is fixed per unit of land.

3.1.2: Net benefits from water use in the residential and non-residential sectors:

The municipal demand for water is divided into residential and non-residential demand, the latter comprising both commercial and industrial water demand. The determination of net benefit functions for residential and non-residential water use follows the point expansion method of water use valuation (Griffin, 2006). The point expansion methodology with a mathematical programming model has been widely used in studies on urban water demand (Booker et al., 2012; Ward et al., 2006). It relies on a given elasticity estimate for urban residential/ non-residential use and a point estimate on the marginal benefit function (observed value of a quantity of water and its corresponding marginal value or price) for a baseline year. In the absence of consistent historical data to estimate urban water consumption for residential and non-residential purposes, this method serves as a suitable technique for our analysis.

For simplicity, water demand in each sector "i" is represented by a linear marginal benefit function having the following form:

$$\hat{p}_i = \hat{a}_i - \hat{b}_i \overline{w}_i$$

Where, $\hat{p}_i$ and $\overline{w}_i$ denote the sectoral level price of water and water use respectively.

A linear marginal benefit schedule implies a nonlinear quadratic total benefit function for water use for each of the residential and non-residential sectors as follows:

$$TB_I(w_i) = \int_0^{w_i^*} \left(\hat{a}_i + \hat{b}_i w_i\right) dw$$

Here, the intercept and slope parameters for the demand function ($\hat{a}_i$ and $\hat{b}_i$respectively) are obtained from calibrating the total benefit function with actual data for water demand, prices or rates per unit of water delivered and costs of water distribution/ delivery. The aggregate net benefit from water use in each sector is then expressed as the joint maximization of the consumer and producer surplus after subtracting the total costs of water delivery for each sector in each region.

For the residential sector (R), the net benefit takes the following form:

$$NB_r^R = \sum_{c=1}^{C} \left[B_r^R\left(w_{cr}^R\right) - C_r^R\left(w_{cr}^R\right)\right] \tag{4}$$

$$(r = 1,2)$$

where $B_r^R(w_{cr}^R)$ refers to the total benefit from residential (R) water use in each city “c” in region "r" and $C_{cr}^R(w_{cr}^R)$ denotes the total cost of residential water delivery in region r. Similarly, the net benefit for the nonresidential sector (NR) takes the following form:

$$NB_r^{NR} = \sum_{c=1}^{C} \left[B_r^{NR}(w_{cr}^{NR}) - C_{cr}^{NR}(w_{cr}^{NR}) \right] \tag{5}$$

$$(r = 1,2)$$

where the terms $B_r^{NR}(w_{cr}^{NR})$ and $C_{cr}^{NR}(w_{cr}^{NR})$ have the same interpretations as above, except that they denote nonresidential water use in each city of region r.

As in the agricultural sector, a balance equation, aggregates all of the nonagricultural water use in the regions specified in our model.

$$\sum_{c=1}^{C} w_{cr}^R + \sum_{c=1}^{C} w_{cr}^{NR} = W_{rRNR} \tag{6}$$

$$(r = 1,2)$$

An institutional constraint on the total amount of water W_{rRNR} that may be drawn for both residential and nonresidential purposes in each region r is as follows:

$$W_{rRNR} \leq \overline{W}_{rRNR} \tag{7}$$

$$(r = 1,2)$$

3.2: Waste water relationships

The next step in our conceptual model is to relate the flow of wastewater from the non-agricultural sectors to the treatment plants located in both regions. First, it is assumed that a definite proportion of non-agricultural water use is translated into wastewater every year. Secondly, out of the total amount of wastewater generated from each region, a certain proportion flows to the wastewater treatment plant. For the sake of having a simple framework, the proportions are considered predetermined or exogenous to the model, but may be endogenized by changing the cost of treatment and the optimal choice of treatment facilities/plants.

The wastewater flow relationship may be expressed as

$$W_{rW} = \delta W_{rRNR} \tag{8}$$

$$(r = 1,2)$$

where δ represents the proportion of residential and nonresidential water that is converted to wastewater flow in each region. In addition, a finite proportion of the wastewater flow is sent to one or both of the wastewater treatment plants. For instance, Nogales, Sonora can send its wastewater flow to either the NIWTP or the LAWTP. Let θ $(0 \leq \theta \leq 1)$ denote the proportion of the wastewater flow from Nogales, Sonora being transferred to LAWTP and W_{LAW} denote the total amount of wastewater flow. Then we have:

$$W_{LAW} = \theta W_{1RNR} \tag{9}$$

The wastewater flows to the NIWTP originate from both Nogales, AZ and Nogales, Sonora. Let parameter α denote the proportion of the wastewater flow from Nogales, AZ that is transferred to the NIWTP. Thus, the total wastewater flow (W_{NW}) being transferred to NIWTP becomes:

$$W_{NW} = (1 - \theta)W_{1RNR} + \alpha W_{2RNR} \tag{10}$$

It may be noted that the individual wastewater treatment costs are accounted for in the net benefits from water use in each region and are not explicitly shown to affect the annual level of flow to the treatment plant.

3.3: Stock of water or water supply relationships

Finally, the model is closed by a set of constraints stating that the sector specific water demand in each region cannot exceed the stock of water available from each aquifer. Agricultural sector water demands cannot be satisfied by water from the Los Alisos Aquifer, as has been established from most studies. The constraint for the Los Alisos Aquifer is

$$W_{1RNR} \leq S_1 \tag{11}$$

Where, S_1 refers to the amount of water available from the Los Alisos aquifer.

The water stock constraint for the Santa Cruz aquifer is

$$\sum_{r=1}^{2}(W_{Ar}+W_{rRNR})\leq S_2 \tag{12}$$

Where, S_2 refers to the amount of water available from the Santa Cruz aquifer.

The model objective may then be expressed as:

$$B=\sum_{r=1}^{2}(\pi_{rA}+NB_r^R+NB_r^{NR}) \tag{13}$$

Which is maximized subject to equations (2), (3), (6), (7), (8), (9), (10), (11) and (12) above.

4. Study region and data

For the purposes of our analysis, the study region consists of the Santa Cruz Active Management Area (SCAMA) that covers a portion of the border region in Arizona overlaid by the Santa Cruz (SC) aquifer and the city of Nogales in Mexico. On the Arizona side, we include three major cities —Nogales AZ, Tubac and Rio Rico —within SCAMA and are served by the Santa Cruz aquifer, while Nogales, Sonora is served by the SC aquifer, the Los Alisos Aquifer and to a certain extent by the Nogales aquifer, falls within our study region from the Mexican side of the border.

[*Insert Fig 1 here*]

For SCAMA, agricultural activities consume the largest percentage of water (52%) followed by municipal (40%) and industrial activities. As previously mentioned, the municipal and industrial sectors are disaggregated into residential and non-residential sector in terms of water demand. In the Mexican region, urban water use for residential and non-residential sectors constitutes 78% of total water demand, with agriculture and livestock accounting for the rest.

Since according to current SCAMA regulations, groundwater and surface water are conjunctively managed, no distinction is made in terms of water source. Agricultural water is drawn from irrigation grandfathered groundwater rights, while non-agricultural water (water for residential and non-residential purposes) is drawn from Type I and II rights, domestic wells (exempt) and service area rights[1]. An irrigation grandfathered right confers the right to irrigate specific plots of land that had been irrigated with groundwater between 1975 and 1980. A Type 1 right is associated with land permanently retired from farming and converted to a non-irrigation use, e.g., building a new industrial plant or a subdivision. A Type II right is based on historical pumping of groundwater for a non-irrigation use and equals the maximum amount pumped in any one year between 1975 and 1980. Unlike grandfathered and Type I rights, groundwater may be sold under Type II rights without the associated land (ADWR, SCAMA web link).

We introduce two modifications in our dataset. Due to paucity of data on the actual amount of water drawn and costs of pumping from domestic wells and Type II rights, it is assumed that a substantial portion of non-agricultural water is served by service area rights to which the private water companies have access to. The four largest such companies or water providers namely, the City of Nogales, Valle Verde Water company, Rio Rico Utilities, and Tubac Water Company provide 60% percent of water in the four municipalities of SCAMA, with the City of Nogales providing 52% of municipal water need. Second, though a large proportion (86%) of industrial (non-residential) water is used by turf related facilities (owned by golf courses like the Rio Rico and Tubac golf courses) utilizing Type II rights, benefits from such water use cannot be readily determined. Thus, we include their estimated demand for water (ADWR, 2012), leaving out details about their costs and demand functions[2].

For Nogales, Sonora, water services are more centralized in nature with water use regulated by CONAGUA, which is the source of our data for sectoral level demand for water. However, a large proportion of water is drawn from privately owned wells (Camp et al., 1997;

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[1] All of these rights and permits have a water allotment associated with them (ADWR, 2012) which were captured by the institutional water allocation equations in Section 3 above.

[2] Determination of turf related benefits from water use is not so straightforward, especially due to these users exercising their own pumping rights which do not require reporting under prevalent groundwater management rules.

Garcia Rojas, 2005), which usually go unreported (since they are out of service connections) and so it was not possible to impute values to such water use.

The parameters measuring the proportion of wastewater going from each region to the treatment facilities are drawn from published literature (Prichard et al. 2010; Camp et al., 1997) and annual municipal water use report submitted to ADWR for 2010. For instance, it is 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 (Camp et al., 1997). It is further assumed that while the total wastewater from Nogales, AZ reaches the Nogales International Wastewater Treatment plant (NIWTP), for Nogales, Sonora, 60% of the wastewater reaches NIWTP and the rest is treated at the newly constructed Los Alisos Water Treatment Plant (Prichard et al., 2010).

Economic parameters

Though most of the economic parameters pertain to the baseline year of 2010, some prices and costs are adjusted to reflect the base year values.[3] In the agricultural sector, parameters like crop level prices, land in production and input costs as obtained from the Food and Agricultural Policy Research Institute (FAPRI), United States Department of Agriculture (USDA-NASS) and National Institute of Statistics and Geography (INEGI), are used for calibrating the functional forms in Section 3 to observed data in each region[4]. While the Mexican data is reported for 2010, from the AZ side, data on a three year average yield and three year average of land acreage devoted to irrigated crops (USDA-NASS) are retained for the initial calibration. The baseline year calibration generates values for the slope coefficient and the intercept term (B_1 and B_0 respectively) for the quadratic crop yield or demand function defined in (3.1) above.

Sectoral level average consumption of water for the baseline year is available from the Arizona Department of Water Resources (ADWR) for the AZ region and from INEGI for Nogales, Sonora. Individual utility company data is used for deriving the marginal water prices

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[3] For instance, some sectoral level water prices and costs are available for 2009 or 2008 and the values are adjusted to 2010 dollars.

[4] While yield data is obtained from USDA Ag Census, data for crop acres comes from the USDA Cropland Data Layer and is validated through the five year Ag Census data for AZ.

(or rates) for the baseline year. Since in most cases, the rate structure varies with the type of water use (residential or commercial), we utilize previous data on volumetric consumption to compute water rates charged in each sector.

However, for obtaining a definite point elasticity of demand for water we resort to recently published estimates for residential and non-residential water demand for each region. These estimates are chosen based upon similarities in socio economic and demographic characteristics between the sampled populations in each study and our study region. For Nogales, AZ, we select the elasticity of demand for water from Yoo et al. (2014), while the studies by Grafton et al. (2009) and Garcia Salazar et al. (2006) provide pricing and elasticity estimates for residential water consumption in Mexico. The elasticity estimates for non-residential water use are obtained from studies by Renzetti (1992, 2002) and Garcia Rojas (2005), respectively for Nogales, US and Nogales, Mexico.

Tables A1 and A2 in the appendix present the economic and demographic parameters considered for our study region. The demographic parameters for AZ and Nogales, Sonora are obtained from the US Census Bureau /American Community Surveys (2010-2014) and from INEGI (2010) respectively.

As shown in the table below (stock of water available), the Santa Cruz aquifer supplies water to the AZ side of the border, while Nogales, Sonora draws water from three aquifers — Santa Cruz, Los Alisos and Nogales — with the largest percentage of water (72%) drawn from the Santa Cruz aquifer. Institutional regulations dictate that a certain percentage of the water available from these aquifers in each region may be extracted for agricultural and non-agricultural activities. For SCAMA, values for total water permitted to be drawn for the above activities are taken from ADWR (2012) conforming to Assured Water Supply (AWS) rules for Active Management Areas. For Nogales, Sonora, the values for maximum amount of water allowed to be extracted are obtained from CONAGUA (2010).

Table 1: Sources of water supply in the study region

	Aquifer stock	
	AZ	Sonora
	(acre feet)	**(acre feet)**

Santa Cruz	39,600 –142,900	24555.28
Los Alisos	0	8685.33
Nogales	0	915.89

5. Results and Discussions

Baseline

The results for the baseline or benchmark scenario are summarized in Tables 2 and 3 below. Table 2 depicts the water use for agriculture and the net benefits from that sector for the baseline year. In terms of yield per acre, alfalfa and barley and sorghum are found to be the leading crops in the AZ side and Nogales, Sonora respectively; however, total water use in agriculture is low and net benefits from that sector are very small in both regions. Though economic benefits from agriculture is not so high in the study region, the results underestimate actual water use in the sector, particularly because a large portion of agricultural water is devoted to grassland and evergreen shrublands (USDA CDL, 2010). As far as water in the other two sectors use is concerned, non-residential use is found to be almost half of the total water use in the residential sector in SCAMA, though the results do not reflect turf related water use for Rio Rico and Tubac accounting for about 1500 acre feet in 2010. In contrast, optimal residential water use exceeds that of the non-residential sector by almost 90% for Nogales, Sonora.

[*Insert Tables 2 and 3 here*]

Residential water use accounts for 47% and 81% of the total water use in SCAMA and Nogales, Sonora respectively, with net benefits from water use in the residential sector amounting to $3.68 million in SCAMA and $11.22 million in Nogales, Sonora. The net benefits from the non-residential sector is 60% of the residential water use benefits in SCAMA, while in Nogales, Sonora the non-residential benefits constitute only 6.14% of the net benefits from the residential sector. Overall, agriculture seems to have the lowest net benefits as well as the lowest optimal level of water use in both regions.[5]

The results above may be treated as lower bounds for water use benefits, especially for agriculture. First, water use being assumed to be fixed per unit of land though a tenable assumption at the regional level, may mask inefficiencies in water application and/or technology in both cases. Secondly, the low benefits from agricultural water use in Nogales, Sonora may be driven by the absence of actual data on non-irrigation costs in Sonora for which data from the US was used as a proxy. Also, delivery costs of water in the residential and non-residential sectors are high enough to offset some of the expected (high) marginal returns from water use in the non-residential sectors in both AZ and Nogales, Sonora. Nevertheless, these baseline results suggest that population and the resultant high demand for water is reflected in the increased water allocation towards the residential sector.

The optimal level of wastewater flows from Nogales, AZ to NIWTP, as suggested by the baseline model, conforms to the level observed for 2010 data. However, for Mexico, the wastewater flow to NIWTP and LAWTP are found to be lower than the estimated annual flows as reported by ADWR.[6]

Scenarios

Climate variability and drought

The Santa Cruz Basin on both sides of the border experiences an arid climate with an average annual precipitation of around 14.13 inches (NCDC) over Nogales and Rio Rico in AZ and wide variation in streamflow (ADWR). On the Mexican side, several studies have pointed towards very low precipitation (less than 5 inches on an annual average—Prichard et al., 2010) and high temperatures in the next few decades.

Severe water shortages stemming from expanding population especially in Nogales, Sonora is compounded by prolonged heatwaves and variability in surface water flows. The latter

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[5] One limitation of utilizing fixed water per unit of land is underestimating the intensive margin of agricultural water use, which may have an impact upon the results.

[6] The percentage difference is not remarkable and part of the reason why we find a lower amount of wastewater flow in this study may have to do with lower non-residential water use. Due to lack of accurate data on the types on non-residential units in Nogales, Sonora and their actual water use, baseline results are slightly underestimated. We run a sensitivity test later to predict what happens if the number of non-residential units in Sonora increases.

often results in low levels of groundwater recharge especially during dry seasons, even when over pumping from wells reduces the average depth of water (ADWR, 2007). Since surface water and groundwater are hydraulically connected, variability in streamflow translates into variability in groundwater levels through reduction in recharge and tributary underflows (ADWR, 2012; Cobourn, 2015; Shamir et al., 2015).

In this scenario, we consider drought related water shortages as manifestations of climate variability in the study region. High average temperature and low precipitation are both negatively correlated with streamflow in the Santa Cruz River Basin and since groundwater is the primary source of water for all sectors in the region, low surface water flows affect the total stock of water available.[7] The amount of water that actually percolates underneath the ground is determined to a large extent by the relative depth of the water table, with a shallow aquifer having a higher probability of being recharged by surface flows. This is true on both sides of the border, because of the wells being over pumped (ADWR, 2012; Prichard and Scott, 2013). As streamflow recharge varies during drought, so does the amount of water available in the aquifer.

To estimate the variability in streamflow recharge during drought, we draw data from stochastic recharge levels during dry periods (ADWR, 2012). These stochastic recharge values are determined through simulating total natural streamflow recharge from 2011-2025, utilizing historical observations on recharge values over 1985-2010. An upper and lower level of confidence (at a 5% level of significance) are constructed around the mean recharge value to arrive at two different recharge levels with varying water shortages. The upper level denotes a moderate drought while the lower level refers to severe drought related water shortages. For the Nogales, Sonora region, without any access to stochastic recharge data, groundwater availability from the Santa Cruz (SC) aquifer was varied through changes in the recharge levels by 10 % and 30%, with the former indicating moderate drought and the latter indicating severe drought[8]. Our assumptions are not implausible under conditions of severe drought when groundwater depth falls below normal levels on both sides of the border (ADWR, 2007, 2012; Prichard and Scott 2013).

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[7] In SCAMA there is no provision of mitigating low water storage with access to renewable surface water like in the Tucson Active Management Area (TAMA) or other areas having access to CAP water supplies.

[8] This approach conforms to Scott et al. (2010) who state “The generally shallow Mexican portion of the aquifer means that recharge variability translates into water supply variability on an annual basis” (pg.167).

Two drought scenarios are implemented. The first scenario combines severe water shortages for the SCAMA region with a moderate water supply cutback (10%) for the SC aquifer serving the Nogales, Sonora region. The second scenario, on the other hand, captures a severe drought condition for both regions (Nogales, Sonora with a 30% water shortage).

The outcomes on water use and benefits and costs of water allocation in each sector due to water shortages does not differ remarkably from those of the baseline scenario. This is surprising, provided that severe drought conditions are expected to reduce water availability to an extent that it will potentially affect the demand for water and the opportunity costs of water allocation across sectors. However, for both regions, institutional rules laid down by ADWR and CONAGUA give priority to water demand management under supply variability, such that optimal levels of water use are constrained by specified limits. Moreover, as shown in Scott et al. (2012), with changes in both precipitation and recharge levels as well as population in the region over time, reclaimed or treated wastewater may be an alternative source of satisfying increasing water demand, particularly in the Nogales, Sonora side. Since we do not account for this option in our model, sectoral water use gets constrained by external limits set by agencies.

Population growth

One of the major drivers of increased water demand in the Santa Cruz border region has been the high growth rates of population experienced, particularly in the Nogales area of Mexico. As has been reported in Scott et al (2012), the population of Nogales, Sonora has been experiencing a growth rate of 1.6% over the last decades while the Santa Cruz County itself showed about 1.3% growth rate during the same time period. The above figures are used to build up a population growth rate scenario to assess the impact upon water demand and net benefits from water use in each sector over 2025. The population growth for 2025 is projected from the baseline population levels for 2010 for each of the twin cities of Nogales.

Tables 4 and 5 describe the effects of population growth in each of the three sectors. As expected, population growth has no impact on the agricultural sector in each region, but affects the water use and benefits in the non-agricultural sectors. Interestingly, the increase in population in Nogales, AZ raises water use in the residential sector by 11% relative to the baseline, but an increase in population in Nogales, Sonora has almost no change in residential water use. This may be attributed to the fact that Nogales, Sonora already shows the highest optimal level of water consumption for residential purposes in the baseline model. As Scott et al. (2012) opines, higher demand for water as population expands in the area, may be increasingly served by non-aquifer sources like treated wastewater, a provision that is not considered in our present framework. Also the net benefits from water use in the residential sector increases by 8% in SCAMA, while that in the non-residential sector falls by 18%, as compared to baseline values. This distributional change in water allocation and benefits across the two sectors may be explained by the presence of maximum permitted water supply constraints for agricultural and non-agricultural sectors as mandated by current regulations in Arizona. On the other hand, net benefits from water use in the non-residential sector in Nogales, Sonora falls by merely 0.62% from the baseline scenario.

[*Insert Tables 4 and 5 here*]

Population growth and water shortages due to climate variability

The final scenario deals with changes in both population and in water availability. The water supply variability follows from Scenario 1 where the study region is shown to experience moderate to severe drought, depending upon variability in recharge. In this scenario, we include population growth rates from Scenario 2, in order to determine the combined effect of higher demand for water in the face of drought related shortages. Results are summarized in Tables 6 and 7.

[*Insert Tables 6 and 7 here*]

As population grows in both Nogales by magnitudes similar to Scenario 1, optimal water use in the residential sector in SCAMA increases by 11%, as compared to baseline water consumption. However, the same falls by 18% relative to the baseline in Nogales, Sonora. This result, though intuitively difficult to reconcile with the high population growth and resulting water demand, may be explained by the reallocation of water use within the non-agricultural sectors as water shortages affect supply or availability from the Santa Cruz aquifer. Moreover, with high population growth and reduced water availability, a decrease of the order of 18% in residential water use is not unrealistic.[9] The above results hold under moderate to severe

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[9] Email conversations with hydrologists in MX confirms this result as not being too unrealistic with climate variability along with population growth.

droughts as defined by Scenario 1 and in the presence and absence of the institutional constraints in each region. As far as the residential and non-residential net benefits are concerned, the outcomes of this scenario mimic the results depicted in Scenario 2.

The amount of wastewater flowing from AZ and Nogales, Sonora also differs as compared to the baseline levels, with total amount of wastewater generated and flowing to NIWTP from AZ increasing by 7%, while that flowing to NIWTP and LAWTP from the Nogales, Sonora side falling by 15%. The latter is not unexpected, since consumptive water use in the residential sector in Nogales, Sonora falls as compared to baseline optimal water use.

Several interesting discussions emerge from the above results. First, the baseline results imply the importance of residential water demand sector in the study region and how it influences the optimal water use and benefits in each region. Though the low levels of agricultural water use may be an artifact of the model, it does conform to recent studies finding a lower significance of the agricultural sector in this region. Of course, the allocation of water in the non-agricultural sectors exhibit variation due to population growth, while results do not change much due to variability in water supply. One reason for water demand to be less sensitive to supply shortages may be the way climate variability is treated in the model. The model assumes variability in recharge levels, falling short of incorporating actual variability as demonstrated through low precipitation and high temperatures in most climate models. Since the current study seeks to determine the changes in optimal levels of water use and benefits across sectors, and not just focus on long term climate change and water deficits, the outcomes from the different scenarios should be treated as such.

Sensitivity tests

In the baseline model, price elasticities of water demand were selected in order to reflect the demographic composition of the population. SO for instance, with a not so wealthy population in Nogales, AZ and Nogales, Sonora, elasticities higher than unity were taken. However, In order to determine how the results are sensitive to lower price elasticities , the elasticity coefficient for Nogales, Sonora was lowered to 0.44 (Espey et al., 1997). We find slightly higher benefits for the residential sector in the region which is not unexpected as lower elasticity implies people are less likely to be sensitive to prices.

We also modified the number of non-residential units in Nogales, Sonora based upon estimates drawn from INEGI (2008). Interestingly, total sectoral water use fell as number of non-residential units were raised from that in the initial calibration. For the baseline scenario as well as for the other scenarios, we find a reduction in net benefits in the non-residential sector. This implies that growth in the commercial and/or the industrial sectors and net returns from these sectors are negatively impacted by water scarcity and population growth.

6. Equity Issues

Because of data constraints, equity issues have not been modeled, but discussion of equity implications hold priority in such transboundary water issues. As stated above, Nogales Sonora is an urban area with a population close to 300 thousand —almost ten times that of Nogales AZ—and with a projected population growth higher than that of Nogales AZ. Yet, per capita water consumption in Nogales AZ is around four times than that of Nogales Sonora. This in itself, illustrates economic and social disparities across these two cities (Sánchez and Lara, 1992). A reduction of 18%in water optimal residential water use in Nogales Sonora is likely to hit the lower income groups the most because of their lower ability (and capability) to pay. A reduction in water availability may force consumers to purchase more water from private providers at a high cost. (Water delivery trucks are commonly seen in less better-off neighborhoods in developing countries). With population growth and increased water demand, together with higher temperatures as expected by climate variability, water scarcity will get worse and the poor will be affected to a larger extent.

Currently, Mexico sends two thirds of its wastewater to the Nogales International Treatment Plant in Arizona, and literally pays to discharge its water since clean water does not flow back to Mexico. In 2002, the payment was about 200 thousand dollars a year (Sprouse, 2003). Effluent from the treatment plant benefits consumers and ecosystems north of the border. There are several management options for this wastewater. One is that Mexico either claims its clean water; another is that it treats its own wastewater in the Los Alisos Treatment Plant. The former is cost ineffective as transportation of treated water from NIWTP to Nogales, Sonora will face severe obstacles. The latter may save Mexico significant treatment costs and allow it to keep its water for residential or other uses. This in turn would help Mexico reap some benefits since the value of water to Mexico is larger than its treatment costs (Sanchez, 1997). In all cases, this would tilt the balance between these two countries with resulting impacts upon both equity and efficiency that would need to be studied further.

7. Conclusions and further extensions

Transboundary water resource management is a complex problem and as has been demonstrated in several river basins spanning the US- Mexico border, it is usually exacerbated by a host of physical, economic and institutional factors. The Santa Cruz River Basin overlapping the twin cities of Nogales in AZ and Sonora epitomizes such a situation, where most policy level studies have emphasized upon better coordination and bargaining mechanisms for border water management. The purpose of this study is to determine how the above factors influence the optimal level of water allocation and use across agricultural, residential and nonresidential sectors, using data from the Santa Cruz Active Management Area in AZ and the city of Nogales in Sonora. The baseline optimization model suggests higher optimal water use and higher net benefits from water use in the residential sector on both sides of the border, while agricultural sector overall shows the lowest net returns from water use.

In order to assess how changes in population and drought related water shortages may affect the relative benefits and costs of water allocation across sectors, the study also constructs three different scenarios. While severe drought related shortages in water surprisingly yielded not very different results from the baseline scenario, a combined population change and water shortage scenario is found to have an increase in residential sector water use in SCAMA by 11% while reducing the same in Nogales, Sonora by 18%, as compared to baseline values. Net benefits from water use in the residential sector in SCAMA also increases by 8% over the baseline.

There are several limitations of the current study. The study makes a very simplifying assumption that commercial and industrial users have similar elasticities of demand for water. Also, due to lack of data on self-owned well pumping, the study confines itself to water supplied by largest providers in each region. Some of the pumping, treatment and water delivery costs for Mexico are adjusted based upon data from AZ. Last, but not the least, the study falls short of modeling treated water as one source of riparian benefits on both sides of the border,, a topic that is beyond the scope of the present analysis but a direction for future research. A dynamic modeling of the stock of water and assessing the impact of the scenarios considered, is also an avenue for further research

This is one of the first studies to attempt an integrated approach for water resource management in the Santa Cruz River Basin and thus, results from this study may be extended by including other parts of the basin, subject to data availability. Nevertheless, it adds to present economic policy debates centered on transboundary water allocation, where the interlinkages amongst institutional regulations, demographics and physical factors like water shortages often play a major role in determining the efficiency and efficacy of water management.

References

Arizona Department of Water Resources. 2012. “Draft Demand and Supply Assessment 1985-2025 Santa Cruz Active Management Area”. 1-130.

Baker, J. S. and D. B. Willis. 2006. “Transboundary Water Resource Management and Conflict Resolution: A Coasian Strategic Negotiations Approach.” *Western Economics Forum,* 5 (2): 29-35.

Bark R.H., G. Frisvold, and K.W. Flessa. 2014. “The role of economics in transboundary restoration water management in the Colorado River Delta.” *Water Resources and Economics,* 8: 43-56.

Booker, J. F. and R.A. Young. 1994. “Modeling Interstate and Intra state markets for Colorado river Water Resources.” *Journal of Environmental Economics and Management*, 26: 66-87.

Booker, J.F. 1995. “Hydrologic and Economic responses of Drought under alternative Policy Responses.” *Water Resources Bulletin,* 31(5): 889-906.

Booker, J.F., R.E. Howitt, A.M Michelsen, and R.A Young. 2012. “Economics and the Modeling of Water Resources and Policies.” *Natural Resource Modeling,* 25: 168-218.

Choudhury, E. and S. Islam. 2015. “Nature of Transboundary Water Conflicts: Issues of Complexity and the Enabling Conditions for Negotiated Cooperation.” *Journal of Contemporary Water Research & Education,* 155: 43-52.

Cobourn, K. M. 2015. “Externalities and simultaneity in surface Water-Groundwater systems: Challenges for Water rights institutions.” *American Journal of Agricultural Economics,* 97(3): 786-808.

Corkhill, F. and L. Dubas. 2007. “Analysis of Historic Water Level Data Related to Proposed Assured Water Supply Physical Availability Criteria for the Santa Cruz Active Management Area: Santa Cruz and Pima Counties, Arizona.” Modeling Report 18.

Dagnino, M, and F.A. Ward. 2012. “Economics of Agricultural Water Conservation: Empirical Analysis and Policy Implications.” *International Journal of Water Resources Development*, 28: 577-600.

Dinar, A., S. Dinar, S. McCaffrey, and D. McKinney. 2013. “Bridges over Water: Understanding Transboundary Water Conflicts, Negotiation and Cooperation.” Second Edition. World Scientific Publishers, Singapore.

Espey, M., J. Espey, and W. D. Shaw. 1997. “Price elasticity of residential demand for water: A meta-analysis.” *Water Resources Research,* 33 (6): 1369-1374.

Fernandez L. 2013. “Transboundary Water Institutions in Action.” *Water Resources and Economics,* 1: 20-35.

Frisvold G.B. and M.F. Caswell. 2000. “Transboundary Water Management: Game-Theoretic Lessons from Projects in the US-Mexico Border.” *Agricultural Economics,* 24: 101-111.

García-Salazar, J.A., E. G.-Soria, and M. F.-Hernández. 2006. Water Demand and Distribution in the Comarca Lagunera, México.*Agrociencia,* 40: 269-276.

Gohar, A.A. and F.A. Ward. 2010. “Gains from expanded irrigation water trading in Egypt: An Integrated basin approach.” *Ecological Economics*, 69: 2535-2548.

Gohar, A.A., F.A. Ward and A.A. Amer. 2013. “Economic performance of water storage capacity expansion for food security”. *Journal of Hydrology*, 484: 16-25.

Grafton, R.Q., T. Kompas, H.T., and Ward, M. 2009. “Residential Water Consumption: A Cross-Country Analysis.” Environmental Economics Research Hub Research Reports, Research Report No. 23.

Griffin, R.C. 2006. *Water Resource Economics: The Analysis of Scarcity, Policies, and Projects*. Cambridge, MA: The MIT Press.

Guerrero Garcia Rojas, H. 2005. “Industrial Water Demand in Mexico: Econometric Analysis and Implications for Water Management Policy.” Pour le Doctorat en Sciences Economiques, Universite de Toulouse 1-Sciences Sociales

Harou, J.J., J. Medellín-Azuara, T. Zhu, S. K. Tanaka, J. R. Lund, S. Stine, M. A. Olivares, and M. W. Jenkins. 2010. “Economic consequences of optimized water management for a prolonged, severe drought in California.” *Water Resources Research*, 46: 1-12.

Howitt, R.E. 1995. “Positive Mathematical Programming.” *American Journal of Agricultural Economics*, 77: 329-342.

Howitt, R. E., J. Medellín-Azuara, D. McEwan, and J. R. Lund. 2012. “Calibrating disaggregate economic models of agricultural production and water management.” *Environmental Modeling & Software*, 38, 244-258.

Ingram, H., and D.White. 1993. “International Boundary and Water Commission: An Institutional Mismatch for Resolving Transboundary Water Problems.” Natural Resources Journal, 33: 153-176.

Maneta, M. P., M. O. Torres, W. W. Wallender, S. Vosti, R. Howitt, L. Rodrigues, L. H. Bassoi, and S. Panday. 2009. “A spatially distributed hydroeconomic model to assess the effects of drought on land use, farm profits, and agricultural employment.” *Water Resources Research*, 45:1-19.

Megdal S.B. and C.A. Scott .2011. “The importance of institutional asymmetries to the development of binational aquifer assessment programs: the Arizona-Sonora experience.” *Water*, 3:949–963.

Millman A. and C.A. Scott. 2010. “Beneath the surface: intra national institutions and management of the United States—Mexico transboundary Santa Cruz aquifer.” *Environmental Planning and Government Policy*, 28: 528−551.

Nakao, M., D. Wichelns, and J. Montgomery. 2002. “Game Theory Analysis of Competition for Groundwater Involving El Paso, Texas and Ciudad Juarez, Mexico.” Paper presented at “Moving with the Speed of Change,” the 2002 Annual Meeting of the American Agricultural Economics Association in Long Beach, CA, July 28-31.

Norman, L.M., M.L. Villarreal, R. Niraula, T. Meixner, G. Frisvold and W. Labiosa. 2013. “Framing Scenarios of Binational Water Policy with a Tool to Visualize, Quantify and Valuate Changes in Ecosystem Services”. *Water*, 5: 852-874.

Prichard, A., C. Scott, P. Vandervoet, S. Megdal. 2010. Drought and Urbanization: Water Supply Challenges of Nogales, Sonora. Arizona Hydrological Society Symposium, September 1-4.

Prichard, A., and C. Scott. 2013. "Interbasin water transfers at the US–Mexico border city of Nogales, Sonora: implications for aquifers and water security". *International Journal of Water Resources Development*, 0:1-17.

Renzetti, S. 1992. "Estimating the Structure of Industrial Water Demands: The Case of Canadian Manufacturing." *Land Economics*, 68: 396-404.

Renzetti, S. 2002. *The Economics of Water Demands*. Boston: Kluwer Academic Publishers.

Sánchez, R. 1997. "Water conflicts between Mexico and the United States: Towards a Transboundary Regional Water Market?", in *The Scarcity of Water: Emerging Legal and Policy Responses*. E. Brans, E. de Haan, A Nollkaemper, and J. Rizema (Ed.). London: Kluwer Law International.

Sánchez, R. and F. Lara. 1992. "Manejo Transfronterizo del Agua. Estrategias y opciones para Nogales Sonora. Nogales. El Colegio de la Frontera Norte.

Scott C.A.**,** S. Megdal, L.A. Oroz, J. Callegary, and P. Vandervoet. 2012. "Effects of climate change and population growth on the transboundary Santa Cruz aquifer." *Climate Research*, 51, 151-170.

Shamir, E., S.B.Megdal, C.Carrillo, C.L.Castro, H.I Chang, K.Chief, F.E. Cokhill, S. Eden, K.P. Georgakakos, K.M. Nelson, and J. Prietto. 2015. "Climate change and water resources management in the Upper Santa Cruz River, Arizona." *Journal of Hydrology*, 521:18-33.

Soria, E. G., J. A. G Salazar, and M. F Hernández. 2006. Demanda y distribución del agua en la Comarca Lagunera, México. *Agrociencia*, *40*(2): 269-276.

Sprouse, T.W. 2003. "Equitable Management of Mexican Effluent in Ambos Nogales", *Journal of the Southwest*, Vol. 45, No. 4 (Winter): 595-610.

Varady R. G., C. A. Scott, M. Wilder, B. Morehouse, N. Pineda- Pablos , and G. M. Garfin. 2013. "Transboundary adaptive management to reduce climate change vulnerability in the western U.S.–Mexico border region." *Environmental Science and Policy*, 26: 102-113.

Ward, F.A., J.F. Booker and A.M. Michelsen. 2006. "Integrated Economic, Hydrologic and Institutional Analysis of Policy Responses to Mitigate Drought Impacts in Rio Grande Basin." *Journal of Water Resources Planning and Management*, 132(6): 488-506.

Ward, F.A. and M. Pulido-Velazquez. 2012. "Economic Costs of Sustaining Water Supplies: Findings from the Rio Grande." *Water Resources Management*, 26 (10): 2883:2909.

Wilchens, D. 2001."The role of "virtual water" in efforts to achieve food security and other national goals, with an example from Egypt". *Agricultural Water Management*, 49: 131-151.

Yoo, J., S. Simonit, A.P. Kinzig, and C. Perrings. 2014. "Estimating the Price Elasticity of Water Demand: The Case of Phoenix, Arizona." *Applied Economic Perspectives and Policy*, 36: 333-350.

Web links:

American Community Survey Available at: http://www.census.gov/acs/www/

Arizona Department of Water Resources. Available at http://www.azwater.gov/azdwr/

Food and Agricultural Policy Research Institute. Available at http://www.fapri.org/

International Boundary and Water Commission. Available at http://www.ibwc.state.gov/home.html

National Agricultural Statistics Service Cropland Data Layer. Available at https://www.nass.usda.gov/Research_and_Science/Cropland/SARS1a.php

National Agricultural Statistics Service. Available at http://www.nass.usda.gov/

National Climate Data Center. Available at http://www.ncdc.noaa.gov/data-access/land-based-station-data/land-based-datasets/climate-normals/1981-2010-normals-data

National Institute of Statistics and Geography. Available at http://www.inegi.org.mx/

National Water Commission of Mexico. Available at: http://www.conagua.gob.mx/home.aspx

National Population Council of Mexico. Available at http://www.conapo.gob.mx/

Santa Cruz Active Management Area. Available at:

http://www.azwater.gov/AzDWR/WaterManagement/AMAs/SantaCruzAMA/default.htm

Fig 1

Table 2: Agricultural benefits and costs: Baseline

	SCAMA	**SONORA**
cropyield		
Alfalfa (*tons/acre*)	8.55	6.38
Wheat (*bushels/acre*)	133.34	
Barley (*bushels/acre*)	140.98	631.42
Sorghum (*bushels/acre*)		605.48
Landuse (*acres*)		
Alfalfa	319.57	86.50
Wheat	4.97	
Barley	20.39	79.91
Sorghum		112.00
Water use (*acre feet/year*)	2455	1880
Net benefits (*$*)	242649.04	37562.40

Table 3: Residential and Non-residential benefits and costs: Baseline

	Residential			**Non Residential**	
	SCAMA	**SONORA**		**SCAMA**	**SONORA**
residential water use (*acre feet/year*)			**nonresidential water use** (*acre feet/year***)**		
Nogales-AZ	2204.75		Nogales-AZ	1570.21	
Rio Rico	1823.53		Rio Rico	721.36	
Tubac	179.52		Tubac	67.13	
Nogales-MX		14686.13	Nogales-MX		1532.35
total	4207.8	14686.13	**total**	2358.7	1532.35
residential water use costs (*$*)			**nonresidential water use costs** (*$*)		
Nogales-AZ	1684429		Nogales-AZ	1199640.44	
Rio Rico	1393176.92		Rio Rico	551119.04	
Tubac	137153.28		Tubac	51287.32	
Nogales-MX		1.12E+07	Nogales-MX		1170715.4
total	3214759.2	11220200	**total**	1802046.8	1170715.4
wateruse_residential (*acre feet/year*)			**wateruse_nonresidential** (*acre feet/year*)		
	4207.8	14686.13		2358.7	1532.35
net benefits_residential			**net benefits_nonresidential**		($)
(*$*)	3681860.30	1.3E+07	(*$*)	2192670.18	819034.46

Table 4: Agricultural benefits and costs:
Population growth (*Scenario 2*)

	SCAMA	**SONORA**
cropyield		
Alfalfa (*tons/acre*)	8.55	6.38
Wheat (*bushels/acre*)	133.34	0.00
Barley (*bushels/acre*)	140.98	631.42
Sorghum (*bushels/acre*)	0.00	605.48
Landuse (*acres*)		
Alfalfa	319.57	86.50
Wheat	4.97	0.00
Barley	20.39	79.91
Sorghum	0.00	112.00
wateruse		
(*acre feet/year*)	2455	1880
net benefits		
($)	242649.037	37562.4

Table 5: Residential and Nonresidential benefits and costs: Population growth (*Scenario 2*)

	Residential			**Non Residential**	
	SCAMA	**SONORA**		**SCAMA**	**SONORA**
residential water use (*acre feet/year*)			**nonresidential water use** (*acre feet/year*)		
Nogales-AZ	2676		Nogales-AZ	1570.21	
Rio Rico	1823.53		Rio Rico	721.36	
Tubac	179.52		Tubac	67.13	
Nogales-MX		14686.13	Nogales-MX		1532.35
total	4679.05	14686.13	**total**	2358.7	1532.35
residential water use costs (*$*)			**nonresidential water use costs** (*$*)		
Nogales-AZ	2044464		Nogales-AZ	1199640	
Rio Rico	1393177		Rio Rico	551119	
Tubac	137153.3		Tubac	51287.32	
Nogales-SON		1.12E+07	Nogales-MX		1170715
total			**total**		
net benefits_residential			**net benefits_ nonresidential**		
(*$*)	4000375	1.33E+07	(*$*)	1795990	813893.3

Table 6: Agricultural benefits and costs : Population growth and water shortages (*Scenario 3)*

	SCAMA	**SONORA**
cropyield		
Alfalfa (*tons/acre*)	8.55	6.38
Wheat (*bushels/acre*)	133.34	0.00
Barley (*bushels /acre*)	140.98	631.42
Sorghum (*bushels /acre*)	0.00	605.48
Landuse (*acres*)		
Alfalfa	319.57	86.50
Wheat	4.97	0.00
Barley	20.39	79.91
Sorghum	0.00	112.00
wateruse_agriculture *(acre feet/year)*		
	2455	1880
net benefits_agriculture ($**)**		
	242649	37562.4

Table 7: Residential and Nonresidential benefits and costs : Population growth and water shortages (*Scenario 3*)

	Residential			Non Residential	
	SCAMA	**SONORA**		**SCAMA**	**SONORA**
residential water use (*acre feet/year*)			**nonresidential water use** (*acre feet/year*)		
Nogales-AZ	2676.09		Nogales-AZ	1570.21	
Rio Rico	1823.53		Rio Rico	721.36	
Tubac	179.52		Tubac	67.13	
Nogales-SON		12183.96	Nogales-SON		1532.35
total	4679.14	12183.96	**total**	2358.7	1532.35
residential water use costs (*$*)			**nonresidential water use costs** (*$*)		
Nogales-AZ	2044532.76		Nogales-AZ	1199640	
Rio Rico	1393176.92		Rio Rico	551119	
Tubac	137153.28		Tubac	51287.32	
Nogales-SON		9308545	Nogales-SON		1170715
total			**total**		
net benefits_residential		($)	**net benefits_nonresidential**		($)
(*$*)	4000435.52	1.11E+07	(*$*)	1795990	813893.3

Appendix

A:

In accordance with the Ricardian theory of rent where crop yield is subject to diminishing returns to heterogeneous land quality, we assume the following crop response function

$$yield = B_0 + B_1 * Land \qquad (1)$$

where, crop yield ($yield$) declines with expansion of land acreage ($Land$) . This specification assumes a fixed ratio of irrigation water being applied per unit of land, such that the total water applied per crop equals the proportion of water applied per acre (B_w) times the total land acreage. Thus, land takes on the role of the dependent variable as given by

$$Land = \frac{Water}{B_w} \qquad (2)$$

Substituting the above expression into the yield equation (1), we obtain

$$yield = B_0 + B_1 * \left(\frac{Water}{B_w}\right) \quad (3)$$

The net profit level of the agricultural water user, may be expressed as a function of the land in production in the following manner

$$\pi = (P_k * yield - C) * Land - P_w * water \quad (4)$$

where, P_k is the crop price, C denotes the non-irrigation costs of production and P_w is the price of irrigation water

Substituting the expression for crop yield from (3), we may rewrite the profit level as:

$$\pi = \left[P_k * \left(B_0 + B_1 * \frac{Water}{B_w}\right) - C\right](Water/B_w) - P_w * water \quad (5)$$

The only unknown parameters in the above function are the intercept (B_0) and slope(B_1).

This last expression when differentiated with respect to water applied, synopsizes the classical microeconomic theory of water use being expanded until the value of the marginal product of water equals the price of water. It forms the basis of our baseline PMP calibration, which recovers the estimates of B_0 andB_1, based on observed data on the known parameters.

B:

Let i $(i = 1, \ldots, N)$ denote the category or sector of water use, w_i the quantity of water used in sector i, and $MB_i(w_i)$ the marginal benefit function for water use, in sector i. We assume that the marginal benefit function or the inverse demand for water is linear, so that

$$MB_i(w_i) = a_i + b_i w_i \tag{6}$$

We also note that

$$\frac{dMB_i(w_i)}{dw_i} = b_i \tag{7}$$

Let the price elasticity of demand for water coefficient be denoted as ε_i. This elasticity coefficient is defined as

$$\varepsilon_i = \frac{dw_i}{dMB_i(w_i)} \frac{MB_i(w_i)}{w_i} \tag{8}$$

Using equation (2) to rewrite equation (3), we obtain the following:

$$\varepsilon_i = \frac{1}{b_i} \frac{MB_i(w_i)}{w_i} \tag{9}$$

The parameters a_i and b_i may now be determined by the point expansion process. First, we can solve equation (4) for b_i:, which is the slope of the sectoral water demand function

$$b_i = \frac{1}{\varepsilon_i} \frac{MB_i(w_i)}{w_i} \tag{10}$$

Let the exogenously determined value for the elasticity coefficient be denoted as $\bar{\varepsilon}_i$, the known value for w_i be denoted as $\bar{w}_i$ and the corresponding marginal benefit of water be $MB_i(\bar{w}_i)$. We can substitute these values into equation (10) to compute the slope parameter, $\hat{b}_i$.

The value of the intercept (a_i) can then be obtained by substituting the value of b_i into equation (1) as follows:

$$\hat{a}_i = MB_I(\bar{w}_i) - \hat{b}_i\bar{w}_i \tag{11}$$

Finally, the total benefit function is determined by the area under the marginal benefit function corresponding to the quantity of water consumed in sector i. Let $TB_i(w_i)$ represent total benefits of water consumption for sector i. Integrating the marginal benefit function:

$$TB_I(w_i) = \int_0^{w_i^*} \left(\hat{a}_i + \hat{b}_i w_i\right) dw \tag{12}$$

which generates a quadratic total benefit function for water use in sector i.

[*insert Table A1 here*]

[*insert Table A2 here*]

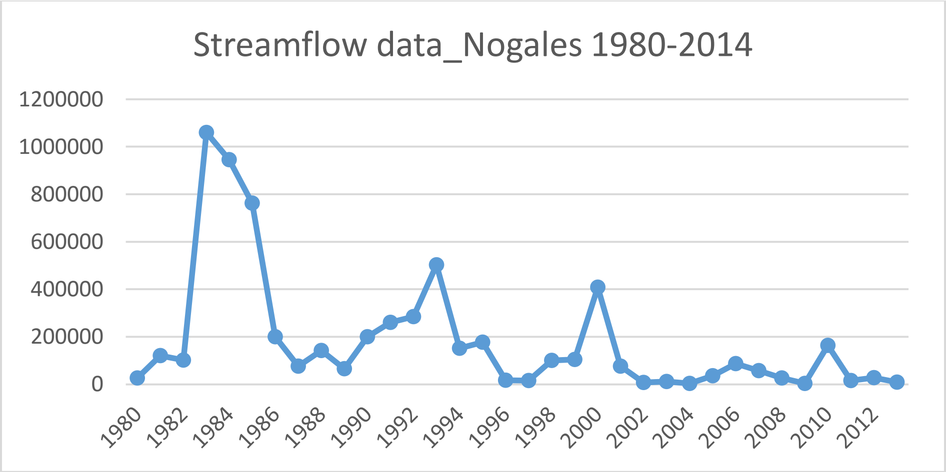
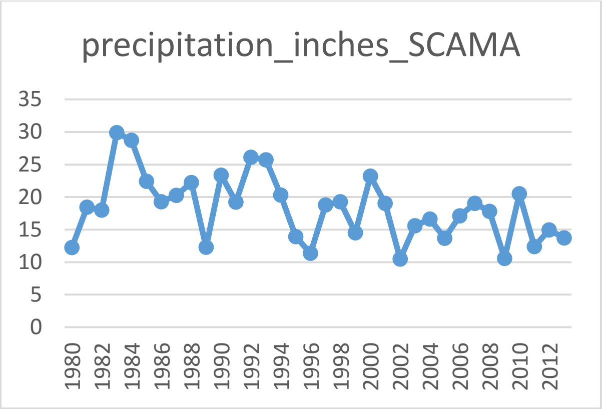


Fig A1



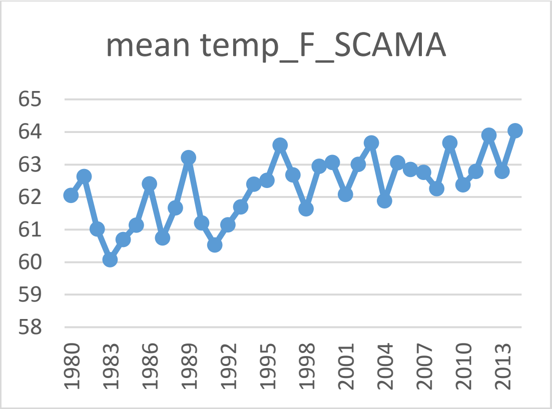


Fig A2

Fig A3

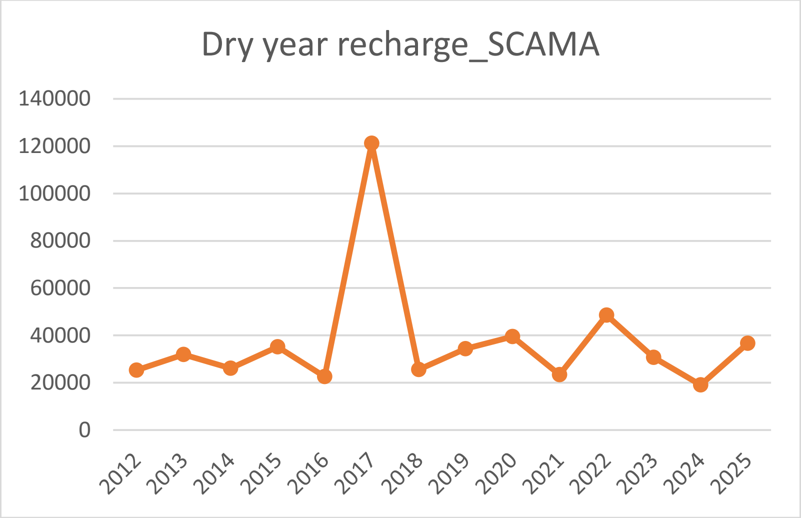


Fig A4