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Impacts of Variable Climate and Effluent Flows on the Transboundary Santa Cruz Aquifer

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Research Impact Statement: Conceptual water budget models are useful to guide and improve decision-making processes in transboundary settings.

ABSTRACT: Assessing groundwater resources in the arid and semiarid borderlands of the United States and Mexico represents a challenge for land and water managers, particularly in the Transboundary Santa Cruz Aquifer (TSCA). Population growth, residential construction, and industrial activities have increased groundwater demand in the TSCA, in addition to wastewater treatment and sanitation demands. These activities, coupled with climate variability, influence the hydrology of the TSCA and emphasize the need for groundwater assessment tools for decision-making purposes. This study assesses the impacts of changes in groundwater demand, effluent discharge, and climate uncertainties within the TSCA from downstream of the Nogales International Wastewater Treatment Plant to the northern boundary of the Santa Cruz Active Management Area. We use a conceptual water budget model to analyze the long-term impact of the different components of potential recharge and water losses within the aquifer. Modeling results project a future that ranges from severe long-term drying to positive wetting. This research improves the understanding of the impact of natural and anthropogenic variables on water sustainability, with an accessible methodology that can be globally applied.

(KEYWORDS: climate variability/change; water policy; transboundary aquifer; groundwater/surface water interaction; effluent; conceptual water budget model; Transboundary Aquifer Assessment Program; Mexico/United States.)

INTRODUCTION

Groundwater is an important source of freshwater for populations and the environment. It serves 45% of human freshwater needs around the world, provides 24% of water for agricultural irrigation, and is a key factor in environmental preservation (Eckstein and Sindico 2014). In the border communities of the United States (U.S.) and Mexico, groundwater from transboundary aquifers usually serves as the primary source of freshwater (Eckstein 2011). Droughts, warming, changes in precipitation patterns, and population growth increase competition for groundwater resources, thereby affecting water availability (Norman et al. 2010b; Scott et al. 2012; Melillo et al. 2014). Evaluating groundwater resources in the arid and semiarid borderlands of the U.S. and Mexico poses a challenge for land and water managers, mostly due to the institutional asymmetries, the lack of binational groundwater management agreements, and the information disparities between the two countries. In this border region and elsewhere, groundwater assessment tools are key to the evaluation of groundwater resources and the development of water management strategies that promote the sustainable use of water resources.

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Groundwater recharge in the Transboundary Santa Cruz Aquifer (TSCA) is highly sensitive to climate uncertainties and physical water and wastewater transfers from both the U.S. and Mexico. The TSCA includes the Santa Cruz Active Management Area (SCAMA) in the U.S. and the Nogales Aquifer and Rio Santa Cruz Aquifer in Mexico (Figure 1). Future climate projections for the Upper Santa Cruz River, north of the Arizona–Sonora border, reveal a possible decline in water reliability, decreased groundwater recharge, and an increase in long-term water deficit (Shamir et al. 2015). Groundwater recharge in this area depends on the highly variable and intermittent natural streamflow events as well as effluent discharge from the binational Nogales International Wastewater Treatment Plant (NIWTP) (Erwin 2007; Shamir et al. 2015).

The NIWTP provides tertiary treatment for the sewage produced in Nogales, Sonora and Nogales, Arizona; together, the cities are often referred to as Ambos Nogales (USIBWC 2005; CH2MHILL 2009). The plant was designed to treat 645 L/s: 211 L/s from the city of Nogales, Arizona and 434 L/s from Nogales, Sonora. However, according to registries from the International Boundary and Water Commission (IBWC), Mexican contributions for 2000–2011 averaged 543 L/s.

In 2012, the Los Alisos Wastewater Treatment Plant (LAWTP) was built to treat excess wastewater that surpasses Mexico's established allotment of 434 L/s. LAWTP has a capacity of 220 L/s and future plans for a 330 L/s expansion. While LAWTP alleviates some of the Mexican wastewater contributions treated within U.S.

FIGURE 1. Study area.

territory, possible variations in effluent discharge from the binational NIWTP, changes in groundwater demand, and changes in Santa Cruz River natural flows might negatively impact the hydrology of the TSCA downstream of the NITWP and affect the management of water resources within this binational region.

Several studies have analyzed the uncertainties associated with the ownership and reuse of sewage and effluent from Nogales, Sonora and Nogales, Arizona (Sprouse and Atondo 2004; Norman et al. 2013; Prichard and Scott 2014); the impact of increased groundwater demands (Erwin 2007; Nelson 2007; Shamir et al. 2007a; Shamir 2017); and the impact of climate uncertainties within different TSCA regions (Norman et al. 2010a, b; Scott et al. 2012; Shamir et al. 2015; Shamir and Halper 2019). Although these studies address some of the main issues concerning land and water management in the area, none of them provide a comprehensive analysis for the effluent-dominated stretch of the TSCA. This study addresses this gap by comprehensively assessing the impact on groundwater recharge of different scenarios of binational effluent discharge, groundwater demand, and climate uncertainties in a portion of the TSCA that is located downstream of the binational NIWTP.

Our approach utilizes a conceptual water budget model and provides an impact assessment of projected climate to understand the nature and implications of climate uncertainties, changes in binational effluent discharge, and changes in groundwater demand within the effluent-dominated portion of the TSCA. We document the process for determining the various components of the conceptual water budget model with a simple approach that can be applied to other areas along the U.S.–Mexico border and around the world; determine the usefulness of this information for the formulation of updated regulations for the SCAMA; and identify water governance gaps within the binational TSCA pertaining the ownership and re-use of the effluent, particularly that owned by Mexico.

For the purpose of this study and in accordance with available literature for the study area (Sprouse and Atondo 2004; Norman et al. 2010b; Norman et al. 2013), the word influent will be used when referring to sewage entering a wastewater treatment facility, whereas effluent will be used to describe wastewater that has been already treated.

PREVIOUS WORK

The different regions encompassing the TSCA have been broadly studied. Scholars have analyzed the impact of urban growth and climate uncertainties within the Ambos Nogales Watershed (Norman et al. 2010b) and the TSCA (Scott et al. 2012). Other research includes climate change projections for the Upper Santa Cruz River within the context of water management regimes (Shamir et al. 2015; Shamir and Halper 2019) and the impact of urban growth in water quality (Norman 2007; Norman et al. 2008; Norman et al. 2009). Previous flood vulnerability assessments incorporated climate uncertainties (Norman et al. 2010a) and calibration analysis for the region, accentuated its importance for watershed modeling, but suggested that is not essential for examining alternative future scenarios due to climate variability (Niraula et al. 2012; Niraula et al. 2015). Other relevant studies include a modeling framework for water resources planning for the Santa Cruz River (Shamir et al. 2007a, b) and an analysis of binational water policy scenarios to determine the impact of effluent discharge reductions to ecosystem services (Norman et al. 2013). Studies within the Mexican portion of the TSCA include a steady-state model for the western portion of the Santa Cruz River Aquifer in Mexico (Tapia Padilla 2005), a regional hydrogeological assessment of the Santa Cruz River Aquifer (IDEAS 2008), a hydrogeologic characterization of the Santa Cruz River Aquifer (Minjárez Sosa et al. 20111), a study that analyzes the impact of effluent discharge from LAWTP in Los Alisos Aquifer (Meranza-Castillon et al. 2017), and groundwater availability reports (CONAGUA 2015, 2018).

These regional studies have improved the knowledge base of the TSCA by exploring water resources management and availability through different modeling efforts. However, current gaps in knowledge exist related to the joint analysis of the long-term impact of effluent discharge, climate uncertainties, and groundwater pumping downstream of the NIWTP; the implication of these possible changes for groundwater management within the region; and the possible rules and agreements that could mitigate the impact of these changes within the TSCA, which are key contributions of this study.

The TSCA is one of four aquifers currently studied through the Transboundary Aquifer Assessment Program (TAAP), a joint effort between the U.S. and Mexico to evaluate shared aquifers. The "Joint Report of the Principal Engineers Regarding the Joint Cooperative Process U.S.-Mexico for the TAAP" (Cooperative Framework) was signed on August 19, 2009 (IBWC 2009) and serves as a mechanism for cooperation between the two countries (Megdal 2017; Megdal and Petersen-Perlman 2018; Megdal 2019). This study is part of the U.S.-funded TAAP effort. The TAAP Cooperative Framework establishes that transboundary aquifer assessment should be exclusively for the purpose of expanding knowledge (IBWC 2009). Outcomes of the TAAP in the Arizona–Sonora border region include the development of binational studies for the transboundary San Pedro and Santa Cruz Aquifers. The first study was published by the IBWC in both English and Spanish (Callegary et al. 2016). The second study is currently under binational peer review.

SETTING

This study focuses on a portion of the TSCA located within the SCAMA and downstream of the binational NIWTP (Figure 1). Water resources management and availability in this region are tightly linked to the physical characteristics of the binational setting and the different facets of institutional governance, which are described in this section.

Physical Setting

Study Area. From its headwaters in the San Rafael Valley, the Santa Cruz River flows southwards to cross the U.S.–Mexico border into the state of Sonora, Mexico. The river then turns west and returns to the U.S. east of Nogales, Arizona, where it flows north to converge with the Gila River, a Colorado River tributary. Intensive groundwater withdrawal has diminished the perennial character of the Santa Cruz River. However, effluent discharge from the binational NIWTP, sustain a perennial stretch of about 20 km along the River (Sprouse and Atondo 2004; Nelson 2007) (Figure 2).

The TSCA is divided into three administrative regions: The SCAMA in the U.S., and the Nogales Aquifer and Rio Santa Cruz Aquifer in Mexico. Adjacent to the Nogales Aquifer and outside from the TSCA is the Los Alisos Aquifer, which is a source of groundwater for the city of Nogales, Sonora and the place where LAWTP is located. These separate administrative regions serve different populations and exhibit distinct physical characteristics. Therefore, sustainable management practices within the TSCA must consider the complexity of the region.

The Transboundary Santa Cruz Basin (TSCB), which is the term that will be used to describe the binational Santa Cruz watershed and its surficial characteristics, presents an arid to semiarid climate with bimodal precipitation patterns (Peel et al. 2007; Treese et al. 2009). Rainfall conditions are often associated with the summer monsoon (June–August) and winter frontal storms (November–March). The combination of dry periods throughout the year, coupled with these episodic rainfall events, results in changes of streamflow regimes in the study area, ultimately affecting groundwater recharge within the TSCA.

Within the TSCB, the cities of Nogales, Arizona and Nogales, Sonora, often referred to collectively as Ambos Nogales, represent the largest international community on the Arizona–Sonora border. According to the U.S. Census Bureau and INEGI (Instituto Nacional de Estadística y Geografía/National

FIGURE 2. Photographs of the Santa Cruz River downstream of the Nogales International Wastewater Treatment Plant (NIWTP).

Institute of Statistics and Geography), in 2010, Nogales Arizona had 21,000 residents, whereas Nogales, Sonora officially listed 220,292. Another estimate suggests that there were probably 350,000 inhabitants living in Nogales, Sonora during the same period, considering the floating population that temporarily lives in the area (Milman and Scott 2010). Population growth, residential construction, and industrial activities have increased groundwater demands and wastewater treatment demands in the Ambos Nogales region (Norman 2007; Scott et al. 2012). Urban growth projections for Nogales, Sonora indicate that the city will grow to 3.5 times its 2002 size by 2030 (Norman et al. 2010b), adding stress to the limited water resources availability of the region.

Physical Water and Wastewater Transfers. Physical water and wastewater transfers are common in the Ambos Nogales region and constitute a strategy that sustains the water and sanitation needs of the two cities (Prichard and Scott 2014). These transfers consist of physical movements of water and wastewater across different hydrologic and hydropolitical units without changing the legal ownership of the resource. As noted in Table 1, transfers from three different aquifers are needed to sustain groundwater demands from Nogales, Sonora, whereas the city of Nogales, Arizona utilizes groundwater from the microbasins area and the Potrero well field (Figure 1). Wastewater transferred, treated, and released into natural streams in Los Alisos, Mexico and the SCAMA in the U.S. represent a source of groundwater recharge for these regions, yet the volume, timing, and consistency of wastewater transfers are constrained by the Mexican water governance and the binational agreements from both the U.S. and Mexico. Infrastructure conditions also play an important role in these transfers. For instance, a failure at the Mexican wastewater pumping station (*Carcamo de Rebombeo*) lowered the input to the LAWTP in 2018, with the rest of the waste being sent to the NIWTP (Operating Municipal Agency of Potable Water, Sewage and Sanitation in Nogales [OOMAPAS], 2018, personal communication). It is important to note that these physical water transfers do not consider a change of ownership. For example, the proportion of Mexican effluent discharged to the Santa Cruz River in the U.S. is technically owned by the Mexican government and could be reclaimed at any moment.

TABLE 1. Physical water and wastewater transfers in the Ambos Nogales Region.

Recipient	Amount	Source
City of Nogales, Sonora	~251 L/s (OOMAPAS, 2018, personal communication)	Santa Cruz Aquifer, Sonora
	~449 L/s (OOMAPAS, 2018, personal communication)	Los Alisos Aquifer, Sonora
	~635 L/s (OOMAPAS, 2018, personal communication)	Nogales Aquifer, Sonora
City of Nogales, Arizona	~175.8 L/s (ADWR 2012b)	Microbasins area and Potrero well field, Arizona
NIWTP, Arizona	~468 L/s (IBWC records) (average for 1996–2018)	Wastewater from the city of Nogales, Sonora
	~163 L/s (IBWC records) (average for 1996–2018)	Wastewater from the city of Nogales, Arizona
LAWTP, Sonora	~168.75 L/s (Meranza-Castillon et al. 2017) (average for the year 2015)	Wastewater from the city of Nogales, Sonora

Notes: LAWTP, Los Alisos Wastewater Treatment Plant; OOMAPAS, Organismo Operador Municipal de Agua Potable Alcantarillado y Saneamiento/Operating Municipal Agency of Potable Water, Sewage and Sanitation in Nogales; ADWR, Arizona Department of Water Resources; IBWC, International Boundary and Water Commission.

Institutional Setting

The institutional asymmetries between the U.S. and Mexico represent a challenge for binational cooperation regarding water resources (Mumme 1980; Milman and Scott 2010; Megdal and Scott 2011; Callegary et al. 2018). In the U.S., water management follows a decentralized regime, with regulations varying in each of the states (Milman and Scott 2010; Megdal and Scott 2011). Water management in Mexico tends to be centralized, with the National Water Commission (Comision Nacional del Agua [CONAGUA]) serving as the federal entity in charge of surface and groundwater resources.

Within the decentralized U.S. water management system, the 1980 Arizona Groundwater Management Act provides a series of quantified rights for groundwater users within the Active Management Areas (AMAs) where the rights are regulated by the Arizona Department of Water Resources (ADWR) (Megdal 2012). The law also specified water management goals for each AMA (Megdal 2012), including for the SCAMA. The SCAMA has maintaining safe-yield conditions and preventing local water tables from experiencing long-term declines as its primary groundwater management goals (A.R.S. § 45-562C). Safe-yield is defined by Arizona state law as an attempt "to achieve and thereafter maintain a long-term balance between the annual of groundwater withdrawn in an AMA and the annual amount of natural and artificial recharge" (A.R.S. § 45-561). However, this definition has been historically subject to sustainability concerns, for it does not consider the temporal patterns of groundwater withdrawal (Alley and Leake 2004).

ADWR oversees the Assured and Adequate Water Supply Program, a key groundwater regulation that is designed to protect and preserve limited groundwater supplies within the AMAs (ADWR 2020). According to the provisional Assured Water Supply (AWS) rules for the SCAMA, land subdivisions cannot be approved without demonstrating physical water availability, continuous water availability for a 100-year period, legal water availability, financial capability to construct water delivery systems and storage, consistency with the management plan, and consistency with the management goals of the AMA (ADWR 2020). Since the adoption of the AWS and the creation of the SCAMA occurred at approximately the same time, provisional AWS rules for the SCAMA do not fully incorporate its management goals (ADWR 1999).

Although water managers, scientists, and interested stakeholders worked on updating the AWS for the SCAMA, permanent rules have not been finalized due to a statewide gubernatorial moratorium on rule-making that started in 2009 (Eden et al. 2016). When the moratorium is lifted, the permanent rule-making process will benefit from an enhanced understanding of how variations in effluent discharge, groundwater demands, and Santa Cruz River flows affect groundwater availability in the SCAMA. The binational character of the effluent discharge from the NIWTP and their potentially variable releases pose a challenge for the designation of AWS. This is because the proportion equivalent to Nogales, Sonora's inflows belongs to Mexico and cannot be considered as legally available water for the SCAMA, even though it is a source of aquifer recharge and contributes to the physical groundwater availability.

Unlike the U.S. water management system, in which state government has regulatory authority, the Mexican system of water management is far more centralized. CONAGUA was created in 1989 as a centralized agency of the Mexican government to manage and preserve Mexico's water resources (CONAGUA 2007). Mexico's Law of National Waters (LAN) of 1992 consists of a water right system determined within the context of Article 27 of the Mexican Constitution (DOF 1992), which describes that the "ownership of the lands and waters within the boundaries of the national territory is vested originally in the Nation, which has had, and has, the right to transfer title thereof to private persons, thereby constituting private property" (DOF 1917, I–33). Chapter 16 of the LAN (amended in 2004) specifies that when sewage is produced after using national waters and then discharged into natural streams, it becomes the property of the nation. This statement indicates that retaining Mexican sewage within Mexican territory is supported by their regulatory framework.

Binational Setting

Despite the differences between the U.S. and Mexican institutional settings, the IBWC has worked in collaboration with the cities of Nogales, Sonora, and Nogales Arizona, for over 60 years in finding solutions for the treatment and disposal of wastewater produced by Nogales, Arizona and Nogales, Sonora. IBWC is an international body that oversees the application of U.S.–Mexico treaties related to boundary demarcation, national ownership of waters, sanitation, water quality, and flood control in the border region (U.S. IBWC n.d.). The 1944 Water Treaty regarding the "Utilization of Waters of the Colorado and Tijuana Rivers and of the Rio Grande" (1944 Treaty) is the main water-allocating mechanism for the two nations. IBWC works with different institutions to solve any issue that is not directly addressed by the 1944 Treaty on a case-by-case basis. Decisions made by the IBWC are typically recorded through minutes, which can be defined as an interpretation to the 1944 Water Treaty. Several of these minutes have shaped binational cooperation over the Ambos Nogales region, impacting the two nations' sewage disposal, influent and effluent supply (Table 2).

Minute 227 and 276 state that Mexico may dispose of a part or all of the Nogales, Sonora sewage in its own territory, which is consistent with Article 27 of the Mexican Constitution. The agreements also indicate that Mexico reserves the right to reclaim the treated effluent from the NIWTP that is equivalent to the sewage inflow from Nogales, Sonora. Mexican wastewater deliveries to the NIWTP are subject to changes caused by population growth, increase in water demand, infrastructure adequacy, and availability of resources. Institutional agreements between the U.S. and Mexico set up a framework for wastewater deliveries. However, they also open a window for uncertainties associated with the proportion of Mexican effluent that currently feeds a perennial stretch

TABLE 2. Relevant IBWC Minutes for the Ambos Nogales Region.

Minute	Date	Description
602	1958	Joint operation and maintenance of the Nogales International Sanitation Project (IBWC 1958)
227	1967	Enlargement of the international facilities for the treatment of Nogales, Arizona, and Nogales, Sonora sewage (IBWC 1967)
276	1988	Conveyance, treatment, and disposal of sewage from Nogales, Arizona and Nogales, Sonora exceeding the capacities allotted to the U.S. and Mexico at the Nogales International sewage treatment plant, under Minute no. 227 (IBWC 1988)
294	1995	Facilities Planning Program for the Solution of Border Sanitation Problems (IBWC 1995)

of the Santa Cruz River and it is a source of groundwater recharge for the SCAMA.

Influent and Effluent at the NIWTP. The average influent from both the U.S. and Mexico entering the NIWTP is 630 L/s (1996–2018). However, both countries have exceeded their respective allotments of 211 and 434 L/s at some point during this period (Figure 3). To handle excess loading at the NIWTP, an optional bypass to an aerated lagoon was built in 2006 (CH2MHILL 2009). Whenever the NIWTP input exceeds the plant capacity of 645 L/s, the excess wastewater is diverted to the lagoon to undergo a primary wastewater treatment.

The newer LAWTP is a cost-effective alternative to the NIWTP, yet Mexico continues to send wastewater to both plants. Current sewage infrastructure in Nogales Sonora serves 87.9% of the population, and 100% of the sewage is being treated either at the NIWTP or LAWTP (IBWC Mexican Section, 2018, personal communication). According to Valles Delgado (2014) and the Mexican section of the IBWC (2018, personal communication), Mexico pays 0.047 USD/m^3 for treatment of wastewater that is below the 434 L/s allotment and 0.206 USD/m^3 once it surpasses the threshold stipulated by Minute 276. Treating the sewage in excess of the allotment at LAWTP incurs a cost of 0.16 USD/m^3, including pumping and transportation. Although treating the excess wastewater in LAWTP is a cheaper option, the Mexican input to the NIWTP is often higher than the agreed-upon allotment of 434 L/s. The Mexican overflow at the NIWTP is likely related to population increase in Nogales, Sonora and infrastructure challenges in the pumping station that delivers wastewater to LAWTP (OOMAPAS, 2018, personal communication).

METHODS AND DATA

Our approach consists of a conceptual water budget model that incorporates different scenarios of effluent discharge, groundwater demand, and natural river flow in a transboundary aquifer where groundwater storage is highly affected by precipitation variability and water and wastewater management decisions from both the U.S. and Mexico. A conceptual water budget model determines the importance of the different water fluxes and their variability. The model can be used to assess the impact of projected future climate and changes in land use and cover, assess the impact of new water projects at specific locations, and provide a foundation for efficient water management strategies (Xu and Singh 1998; Zhang et al. 2002; Healy et al. 2007; Quinn

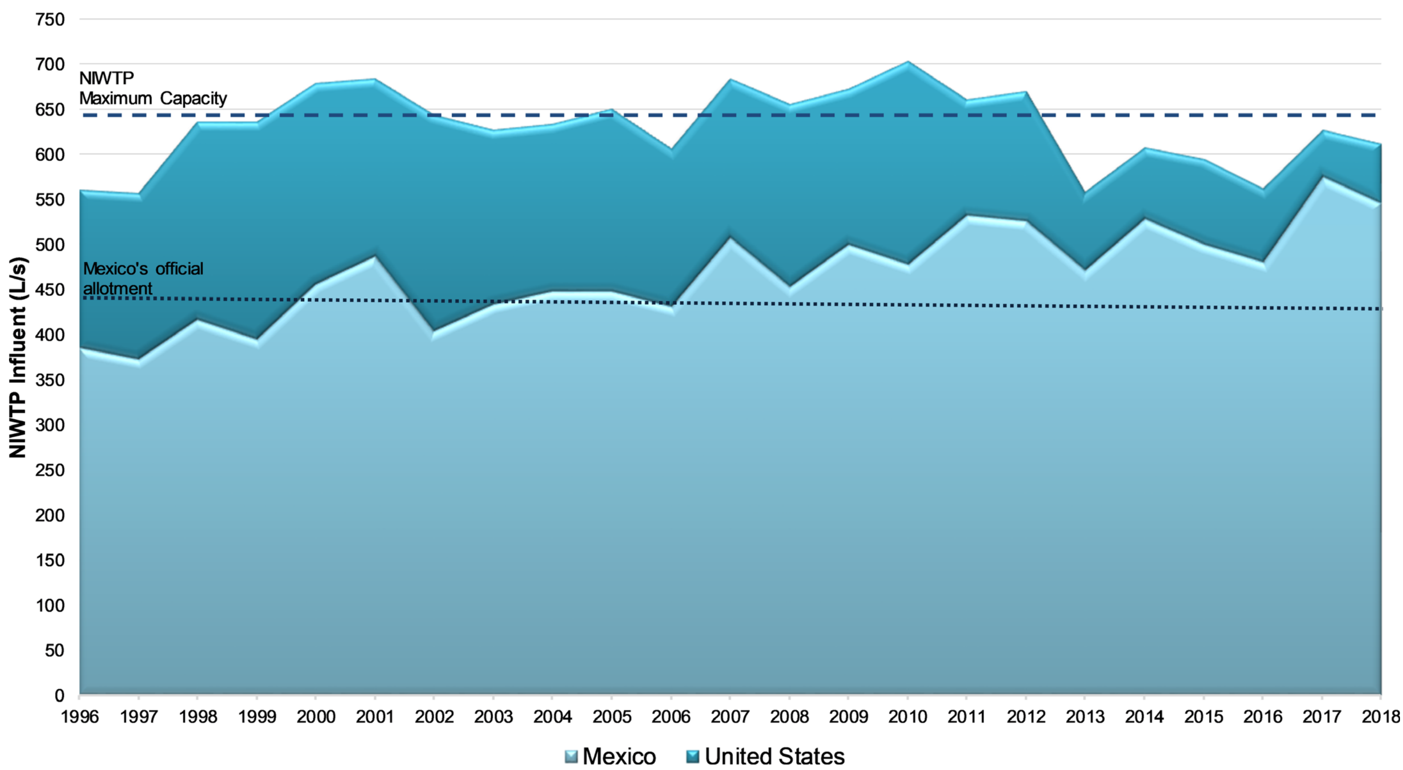

FIGURE 3. NIWTP sewage influent (Mexico, United States [U.S.]).

et al. 2016). A water budget model for a portion of the TSCA that considers the binational character of the aquifer can guide water management decisions by comparing different policy-driven scenarios such as groundwater pumping and effluent discharge.

Development of a Conceptual Water Budget Model

The model considers five sources of aquifer recharge (Nelson 2007): Santa Cruz River natural surface streamflow (SCR_{in}), mountain-front recharge (MFR), effluent discharge from the NIWTP (Eff), incidental agricultural return flow (Ag), groundwater inflow from the tributaries (GW_{trib}), and subsurface inflow from aquifers at the southern boundary of the study area (GW_{in}). Water losses from the study area are attributed to evapotranspiration (ET), withdrawal from wells (P_w), Santa Cruz River streamflow (SCR_{out}), and groundwater exiting the study area at the northern boundaries near the Tucson AMA (GW_{out}).

The water budget equation for the present study conceptual model can be expressed as follows:

$$\begin{aligned} SCR_{in} + MFR + Eff + GW_{in} + Ag + GW_{trib} \\ = ET + P_w + SCR_{out} + GW_{out} + \Delta S, \end{aligned} \tag{1}$$

where ΔS represents the positive or negative change in the aquifer and vadose zone storage.

The conceptual water budget model uses the water budget equation (Equation 1) and treats the entire study region as a single lumped unit. The long-term cumulative change of the aquifer storage calculated by the model is used as a measure to assess whether the prescribed water resources management scheme is a sustainable one. The simulation was implemented at a daily time step to represent the time scale of flow events in the Santa Cruz River, which is likely the most important flux with the highest inter- and intra-annual variability.

The process for determining the various components of the water budget model in a transboundary setting included: a literature review of available hydrologic studies for the region; a set of interviews with members of the U.S. and Mexican sections of IBWC, ADWR, OOMAPAS, and the City of Nogales, Arizona; and a field visit to LAWTP. Personal communication with land and water managers from both the U.S. and Mexico was essential to determine and corroborate the information related to the main components of the conceptual water budget model. Experts were engaged via email, telephone, and face-to-face meetings. Though it took some time to engage stakeholders from two different countries regarding an issue that can be considered politically sensitive like binational wastewater treatment, we had a positive response from most of the parties. Water budget model components can be found on Tables 3 and 4. Additional information about the methods for determining the water budget model components can be found in Appendix 2.

The policy-driven scenarios for this study include groundwater withdrawal management and various effluent discharge scenarios (Tables 3 and 4). Groundwater withdrawal for this simulation is based on average 1997–2002 registries (Nelson 2007) and 2006–2025 projections (ADWR 2012b). For all the eight scenarios of the effluent discharge, we simulated 40-year duration. Each of the eight scenarios is represented as one year of daily flow that is repeated for the 40-year duration of the simulation (Table 3).

The first six effluent discharge scenarios represent the average, maximum, and minimum flows pre and postdevelopment of LAWTP. Scenario seven is equivalent to the U.S.–Mexico established contributions of 645 L/s (20.34 Mm^3/yr). This scenario was developed after several discussions with personnel from the Mexican section of IBWC and OOMAPAS, which revealed that reducing their wastewater inflow to 434 L/s (13.69 Mm^3/yr) is a priority to reduce Mexican treatment costs and to comply with Minute 276. This scenario also considers the 211 L/s (6.65 Mm^3/yr) corresponding to the U.S. agreed upon contributions for Nogales, Arizona. An enlargement to LAWTP to a capacity of 330 L/s and the proper maintenance of the pumping station will help to fulfill this objective at the cost of decreasing some of the Mexican NIWTP influent and therefore, the effluent discharged into the Santa Cruz River in the U.S. Scenario eight is equal to only Arizona's average contributions (1996–2018), a case that considers a halt in Mexican inflows. Even though at this point this might seem an unrealistic scenario, it is a possibility nevertheless, since Minute 226 and 276 establish that Mexico reserves the right to keep wastewater from Nogales, Sonora, within Mexican territory.

Assumptions and Caveats

This water budget model approach allows us to test the water balance of many likely scenarios and for long durations. The scenarios include changes in treated effluent discharge, changes in streamflow, and changes in water demand. We presume that the inflow and outflow components are independent of each other. The water budget model does not account for the groundwater dynamics and assumes that the boundary flow conditions are constant and do not change over time. A dynamic geophysical hydrologic model accounts for changes in the in-and-out fluxes due to dependency on the state of the aquifer. The construction of such a hydrodynamic model requires

TABLE 3. System inflows.

System Inflows	Average (Mm^3/yr)	Source	Notes
Mountain front recharge (MFR)	6.17	Osterkamp (1973), Nelson (2007), ADWR (2012b)	The contribution to the aquifer from recharge along the mountain front. Assumed to recharge the aquifer at a nearly uniform rate
Tributary recharge (GW_{trib})	9.22	Aldridge and Brown (1971), Halpenny and Halpenny (1985), Nelson (2007)	Recharge distributed over 14 tributaries within the study area: 8.14–10.30 Mm^3/yr. In this study, we used an average of 9.22 Mm^3/yr
Santa Cruz River natural flow (SCR_{in})	33.57 Range (0–100)	Based on Shamir (2017), Shamir and Halper (2019)	Estimated Santa Cruz River inflow for 1945–2017 using flow at NIWTP[1] for the winter (October–April) and the flow at the Nogales gauge for the summer (May–September)
Effluent discharge (Eff)	17.44 24.6 12.58 16.02 22.08 14.6 20.34 5.42	Based on IBWC historic registries and interviews with key informants	1. Avg. effluent discharge pre-LAWTP[2] 2. Max. effluent discharge pre-LAWTP 3. Min. effluent discharge pre-LAWTP 4. Avg. effluent discharge post-LAWTP[3] 5. Max. effluent discharge post-LAWTP 6. Min. effluent discharge post-LAWTP 7. Combined U.S.–Mexico agreed-upon contributions 8. Arizona's avg. contributions for 1996–2018
Incidental agricultural return (Ag)	3.65	ADWR (2012a)	25% of irrigated agriculture
Groundwater in (GW_{in})	9.25	Keith Nelson and Olga Hart (ADWR, June 2018, personal communication)	Nelson (2007) estimated consistent subsurface influx to the study region from the Potrero area, Nogales wash, microbasins, and Sonoita Creek

[1]NIWTP, Arizona, Mexico.
[2]pre-LAWTP: Predevelopment of LAWTP, Sonora, Mexico (2000–2012).
[3]post-LAWTP: Postdevelopment of LAWTA, Sonora, Mexico (2013–2017).

extensive datasets for the model parameterizations and observations for the model calibration and validation. With the lack of such detailed datasets, the uncertainty in the hydrodynamic simulations is likely to be comparable to the uncertainty in the simulations of the simplified modeling approach. Moreover, because of the existing low water level conditions of the aquifer in the study area, the changes in the hydraulic gradient between most of the incoming and outgoing fluxes and the aquifer are likely negligible. Therefore, it is reasonable to ignore the dependency of these fluxes on the water level of the aquifer. Thus, given the large uncertainty in many of the boundary conditions processes and the existing aquifer low level, we believe that the independent water balance approach is warranted.

Although some components in Equation (1) are assumed constant and some are varied with time all the inflow and outflow model components are considered as water fluxes. The model fluxes that are likely to have the largest impact on the water balance are the surface flow on the Santa Cruz River from both natural and treated effluent discharge and the water withdrawals. These are also the fluxes that can be reasonably estimated from observed records. The other fluxes are based on estimates from ADWR Modeling Report No. 14, which assumes that these fluxes are persistent from year-to-year (Nelson 2007; ADWR 2012a, b).

The water budget model treats the entire region's water balance as one unit. The region, however, can be divided into two conceptual regions that show very different long-term trends. The first is the southern part of the study area. This region maintains a fairly shallow groundwater level with some sections of perennial flows. The northern section of the study area has a deeper groundwater level and it shows a persistent drop in water levels. The northern area is less affected by the recharge from the treated effluent and likely also dependent on the hydraulic gradient at the boundary with the Tucson AMA (Nelson 2007; ADWR 2012a, b).

Considering the current low water level of the aquifer and the very low likelihood of climatic scenarios that may recharge the aquifer to its full capacity, the absolute storage capacity of the aquifer in the model is unconstrained. This unconstrained aquifer assumption also implies that water withdrawal from the aquifer is unlimited and water withdrawal constraints due to declining water level in the aquifer is not being considered in this model. Therefore, the model simulations and the accumulated change of the aquifer storage should be cautiously interpreted. This is especially true for cases of continuously increasing

TABLE 4. System outflows.

System outflows	Average (Mm^3/yr)	Source	Notes
Evapotranspiration (ET)	16.04 18.5 20.97	Gatewood et al. (1950), S. Masek (unpublished data), Nelson (2007)	Dry season Medium season Wet season
Withdrawal from wells (P_w)	19.49 29.97–28.37	Nelson (2007) ADWR (2012b)	1997–2002 average 2006–2025 projections
Subsurface outflow (GW_{out})	27.14	Olga Hart and Keith Nelson (ADWR, June 2018, personal communication)	Estimated to range between 20.97 and 33.30 Mm^3/yr
Surface outflow (SCR_{out})	10.98	Annual flow at the Amado streamflow gauge (USGS09481770)	Measured at the Amado streamflow gauge during 2004–2009. Record adjusted to remove baseflow that was not apparent after the upgrade to the NIWTP

deficit and decrease in water level, which may introduce conditions in which the withdrawal demand cannot be satisfied by the aquifer.

Projected Future Climate

The impact assessment of projected future climate (2020–2059) is based on precipitation projections from three CMIP5 RCP8.5 global climate models (GCMs): HadGEM2-ES (Global Environmental Model, Version 2) from the United Kingdom Meteorological Office Hadley Centre; MPI-ESM-LR from the Max Planck Institute for Meteorology; and GFDL-ESM2M (Earth System Model) from the NOAA Geophysical Fluid Dynamic Laboratory. These GCMs were selected because of their good performance over North America and because they represent the range of the North America climate sensitivity. The climate projection analysis was conducted for 31.0°–31.75° North latitude and 111.3°–110.3° West longitude, a domain that covers the entire TSCA region.

Since the direct output from GCMs is generally too coarse as input for basin-scale hydrologic modeling, the GCMs required an additional “downscaling” process. In this study, we used two types of downscaling procedures, dynamical and statistical. The dynamical downscaling was received from the North America Coordinated Regional Climate Downscaling Experiment (NA-CORDEX) program (https://na-cordex.org/). These models were downscaled for the domain of the NA-CORDEX program using the Advanced Research version (ARW) of the Weather Research and Forecasting (WRF) Model (Version 3.1) as the Regional Climate Model. The simulations are available for the historic (1950–2005) and future (2006–2100) periods at ~25 km horizontal spacing and at 3- and 6-h intervals for the WRF-HadGEM2-ES, WRF-MPI-ESM-LR, and WRF-GFDL-ESM2M, respectively.

The statistical downscaling is from the state-of-the-art Localized Constructed Analogs (LOCA) (Pierce et al. 2014). LOCA’s leading downscaling assumption is that the forecast will evolve the same way as the best matching historical event. The statistically downscaled simulations are available for 1950–2005 and 2006−2099 at 1/16° (~6 km) horizontal grid spacing at a daily scale. The description of the climate models selection and analyses is detailed in Shamir and Halper (2019) and Shamir et al. (2019).

Water Budget Model Input

The water budget model was developed using seven climate scenarios that included six projected future downscaled climate models (2020–2059) and one historic ensemble. The main model flux that was different in each of these seven scenarios is SCR_{in}, which as discussed above is the dominant and highly variable flux. The development of the SCR_{in} climate scenarios is based on Shamir and Halper (2019), and a short description is provided below.

Rainfall in the Santa Cruz River watershed is highly variable over diurnal, seasonal, and annual scales. This variability gives ground for using of a weather generator to simulate a distribution of model outcomes, rather than a single time series available from the downscaled projections. A weather generator is a probabilistic model that simulates ensembles, each of which consist of a large number of plausible “weather realizations.” In our study, we used the weather generator to produce 100 realizations of hourly precipitation for 40-years. The historic ensemble represents the regional rainfall characteristics, the natural variability, and the uncertainty that is associated with the observed hourly rainfall record. The observed changes between the historic period and the mid-21st Century in the six downscaled projections were used to modify the precipitation weather generator to represent the projected future changes. The modified weather generator was then used to generate hourly precipitation ensembles that represent the projected future changes (2020–2059), as determined by the downscaled projections.

The seven ensembles (each ensemble comprises 100 realizations of hourly precipitation for 40 years), were used as input to a hydrologic modeling framework that simulates streamflow in the Santa Cruz River near the NIWTP. This modeling framework was developed to estimate the groundwater recharge in the alluvial aquifer that is upstream of the study area (the microbasins area) (Figure 1) given various water withdrawal criteria and water management strategies (Shamir et al. 2007a; Shamir et al. 2015; Shamir 2017; Shamir and Halper 2019). The modeling framework includes a routing model that simulates the flow conveyance along the river channel and provides a flow estimate for the Santa Cruz River near the NIWTP (SCR_{in}).

RESULTS

The results of the water budget model simulation, using as input the estimated daily Santa Cruz River streamflow at the NIWTP for 1945–2017 (Table 3; Appendix 2), are shown in Figure 4. The total simulated inflow and outflow components of the average annual mass balance for the study region are 81.77 and 76.1 Mm^3/yr, respectively. This indicates that the average annual inflow and outflow to the study area is balanced, with an annual average gain of about 7%. Note that in this simulation, the Santa Cruz River natural streamflow represents the average estimated annual flow during 1945–2017, the treated effluent discharge is the mean annual discharge for 2000–2017, and the groundwater pumping represents the 1997–2002 average (Nelson 2007).

According to the average annual mass balance simulation for 1945–2017, the Santa Cruz River flows along with the binational effluent discharge for the area represent 65% of the total inflow, while groundwater withdrawal represents 24% of the system outflows (Figure 5). These three components are highly dependent on water management decisions from both the U.S. and Mexico and climate uncertainties, therefore the importance of modeling different scenarios to facilitate decision-making processes for land and water managers. Even though this annual balance indicates there is 5.67 Mm^3/yr excess in storage, it does not represent the large variability in the natural Santa Cruz River streamflow (Table 5). This outcome, however, serves to interpret the significance of the Santa Cruz River inflows for the overall water balance and the importance of analyzing a time series that represents the expected inter-annual variability in the Santa Cruz River streamflow.

In Figure 6 we compare the annual water balance for 1978–2017 using 1997–2002 average groundwater pumping with the 2006–2025 projected pumping (ADWR 2012b). The effluent discharge in this simulation is the average pre-LAWTP scenario. The 1997–2002 average groundwater pumping resulted in groundwater deficit for most of the analyzed years. Only eight out of 40 years ended with a positive water balance while a simulation for 2006–2025 groundwater pumping projections ended with only five years of surplus in storage. Change in storage calculated for the 2006–2025 average groundwater pumping scenario is 60% less than the 1997–2002 scenario. Additionally, given the differences between this multiyear water balance (Figure 6) and the annual mass balance (Figure 4), we stress the importance of considering the inter-annual variability in the Santa Cruz River flows and assessing the water balance in the region with a long-term perspective, which is one of the contributions of this study.

The cumulative 40-year water balance for the eight likely scenarios of effluent discharge and 1997–2002 average pumping indicate that wet years during the mid-1980s created a substantial surplus that has been subsequently depleted (Figure 7). Except for the maximum pre-LAWTP flow, all other scenarios presented a storage deficit by the end of the simulation period. This trend of increased water deficit that follows the wet years of the early 1980s is evident in several wells near the northern boundary of the TSCA aquifer. For example, historical records in the index well D-19-1329BCC near Elephant Head (north of Amado) shows an apparent increase in water level from 1979 until 1995 followed by a constant decrease until 2014 and a slightly increasing trend until 2018 (https://warcat.hrcwater.org/SCAMA/). On the other hand, the cumulative 40-year water balance for the same effluent discharge scenarios and 2006–2025 average pumping projections (ADWR 2012a) shows a significant deficit in water storage that closely doubles the 1997–2002 projections (Figure 6).

The distribution of the annual balance for different effluent discharge scenarios and 1997–2002 average pumping indicates a positively skewed distribution with most of the annual events ending in deficit (Figure 8). The deficit, given that outflows prescribed fixed annual values for ET, pumpage, and groundwater and surface water flowing out, is finite and cannot be lower than about 24.55 Mm^3/yr. The years with water surplus during the mid-1980s are associated with frequent El Niño-Southern Oscillation conditions and positive Pacific Decadal Oscillation (Pool 2005).

Figure 9 shows the cumulative distributions of the water balance by the end of the 40-year period of simulations. It includes the cumulative distribution of the precipitation ensemble that represents the

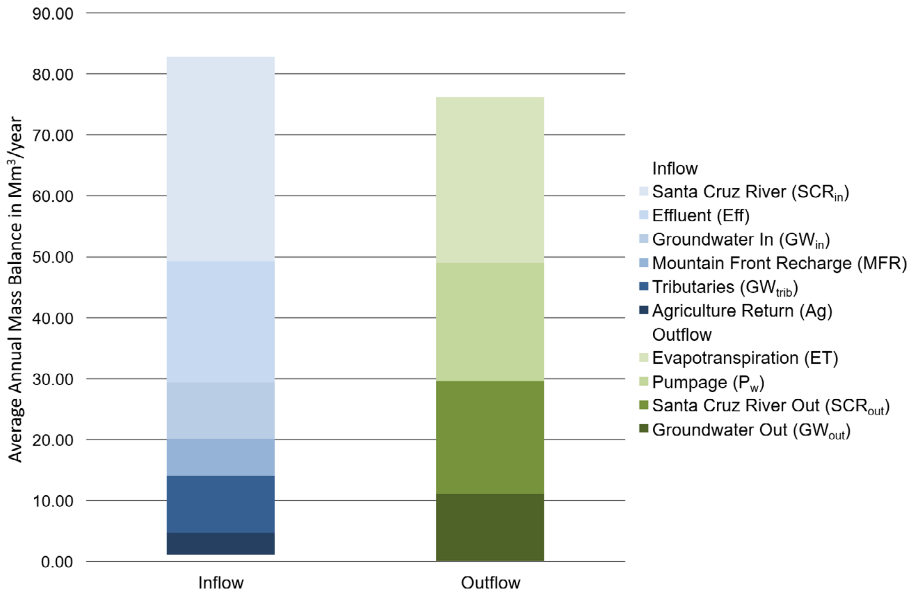

FIGURE 4. Average annual mass balance simulation using the water budget model (1945–2017). In this simulation: SCR_{in} is the daily estimated Santa Cruz River inflow and Eff is the mean annual effluent for 2000–2017. Tables 3 and 4 describe the rest of the inflow and outflow fluxes.

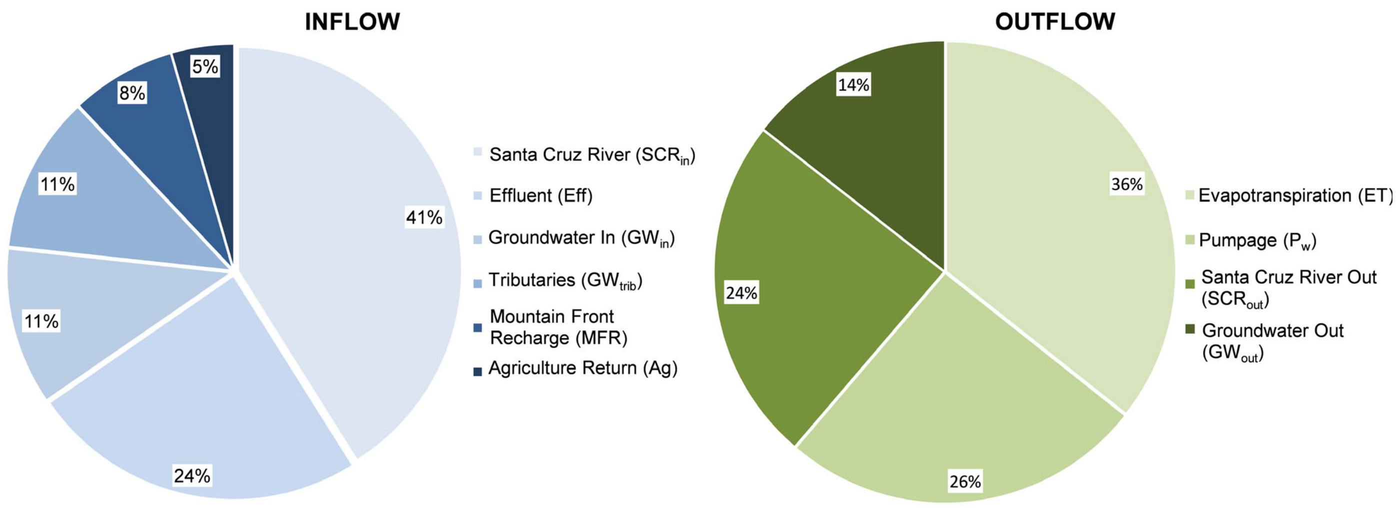

FIGURE 5. Annual percentage of the inflow and outflow fluxes for 1945–2017. In this simulation: SCR_{in} is the daily estimated Santa Cruz River inflow and Eff is the mean annual effluent for 2000–2017. Tables 3 and 4 describe the rest of the inflow and outflow fluxes.

historic period (black) and the single simulation of the nominal case simulated for 1978–2017 (green vertical line), using the mean NIWTP effluent discharge from 2000 to 2012 and from 1997 to 2002 average pumping. Since the analysis of the historic period was carried for a 40-year period, the projected 40-year water balance can be discussed with respect to the historic record. The cumulative distribution of the GFDL-ESM2M simulations closely follows the distribution of the historic ensemble. The MPI-ESM-LR projections indicate drying trends in both the dynamically downscaled and statistically downscaled ranging from about −555 to −246.6 and 0 Mm^3/40-yr, respectively. The largest differences in projections between dynamically downscaled and statistically downscaled are shown for the HadGEM2-ES projections. While the HadGEM2-ES dynamically downscaled showing a wetting trend that ranges from −123.3 to 222 Mm^3/40-yr, the statistically downscaled is showing an overall drying trend with minimum and maximum of about −370 and −61.67 Mm^3/40-yr, respectively. Overall, it is observed that the dynamically downscaled projections yield a wider range of possible scenarios, as compared with the statistically

TABLE 5. Water year (WY) Statistics of 1945–2017 showing the Santa Cruz River natural surface flow at the U.S. Geological Survey (USGS) Nogales gauge, estimated flow at the NIWTP and estimated natural flow at Tubac. Estimated natural flow at Tubac was determined by deducting the discharge of NIWTP treated effluent from the measured flow at the Tubac gauge (USGS 09481749).

Santa Cruz river flow (Mm^3/yr)	**USGS Nogales**	**NIWTP**	**Tubac**
Average	21.62	14.50	33.57
Median	11.44	3.04	22.30
Maximum	109.49	98.91	186.57
Minimum	0.34	0.00	0.86
25 Percentile	4.85	0.00	3.70
75 Percentile	24.73	14.07	46.06
Standard deviation	26.52	24.55	38.31
Coefficient of variation	1.20	1.70	1.10
Skew coefficient	2.00	2.20	2.00

downscaled projections; they project a highly uncertain future that ranges from severe long-term drying to positive wetting.

DISCUSSION

This study utilizes a conceptual water budget model approach to analyze the impact of climate uncertainties and water and wastewater management decisions in a portion of the TSCA located downstream of the binational NIWTP. The conceptual water budget model is a simple and adaptable approach that can be applied over different geographies (Healy et al. 2007). It provides a basic understanding of the region's water fluxes and the change in aquifer storage, information that is useful for decision and policy makers. Our analysis utilizes many of the water budget model inflow and outflow components available in current literature (Erwin 2007; Nelson 2007; ADWR 2012b; Shamir 2017) and adds new "what if" scenarios of effluent discharge, projected groundwater demand (Nelson 2007; ADWR 2012b), and climate projections for 2020–2059. Importantly, this study jointly analyzes these three components.

The results of the water budget model simulation, using as input the estimated daily Santa Cruz River streamflow at the NIWTP for 1945–2017 indicate that the Santa Cruz River natural flows and effluent discharge from the NIWTP account for 65% of inflow to the system, whereas groundwater withdrawal represents about 26% of the outflow. These model fluxes are likely to have the largest impact on the water balance because of their large dependency on climate uncertainties, binational water management decisions, and state water management decisions, respectively.

The largest uncertainty in this study is likely to be introduced by the incorporation of the mid-21st-Century climate projections. Although most of the climate scenarios projected at the median of the cumulative distributions a dryer future, one of the six scenarios projected a wetter future (Hadley dynamically downscaled). In fact, looking at the entire cumulative distribution of the ensembles show that all six-climate scenarios have some likelihood to have a wetter future. This analysis although do not provide a clear trend of drying or wetting, it provides important information for the uncertainty range that should be considered by water resources planners.

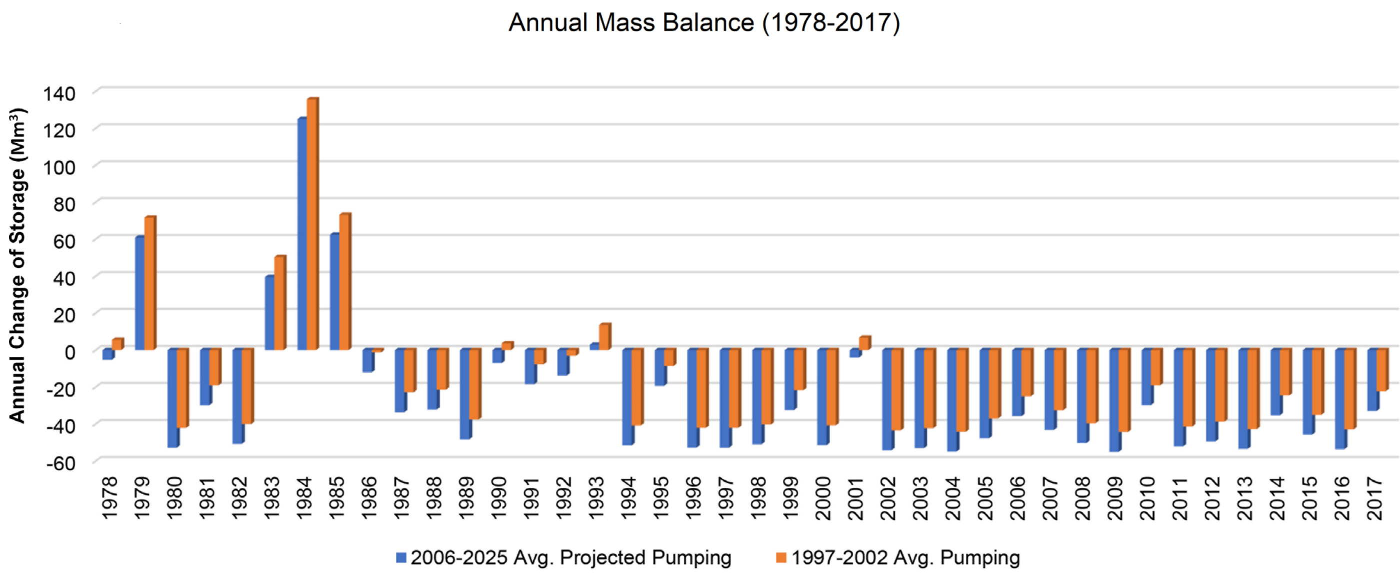

FIGURE 6. Annual water balance calculated for 1978–2017 forced with 1997–2002 and 2006–2025 groundwater pumping average scenarios. Eff corresponds to the average pre-LAWTP scenario.

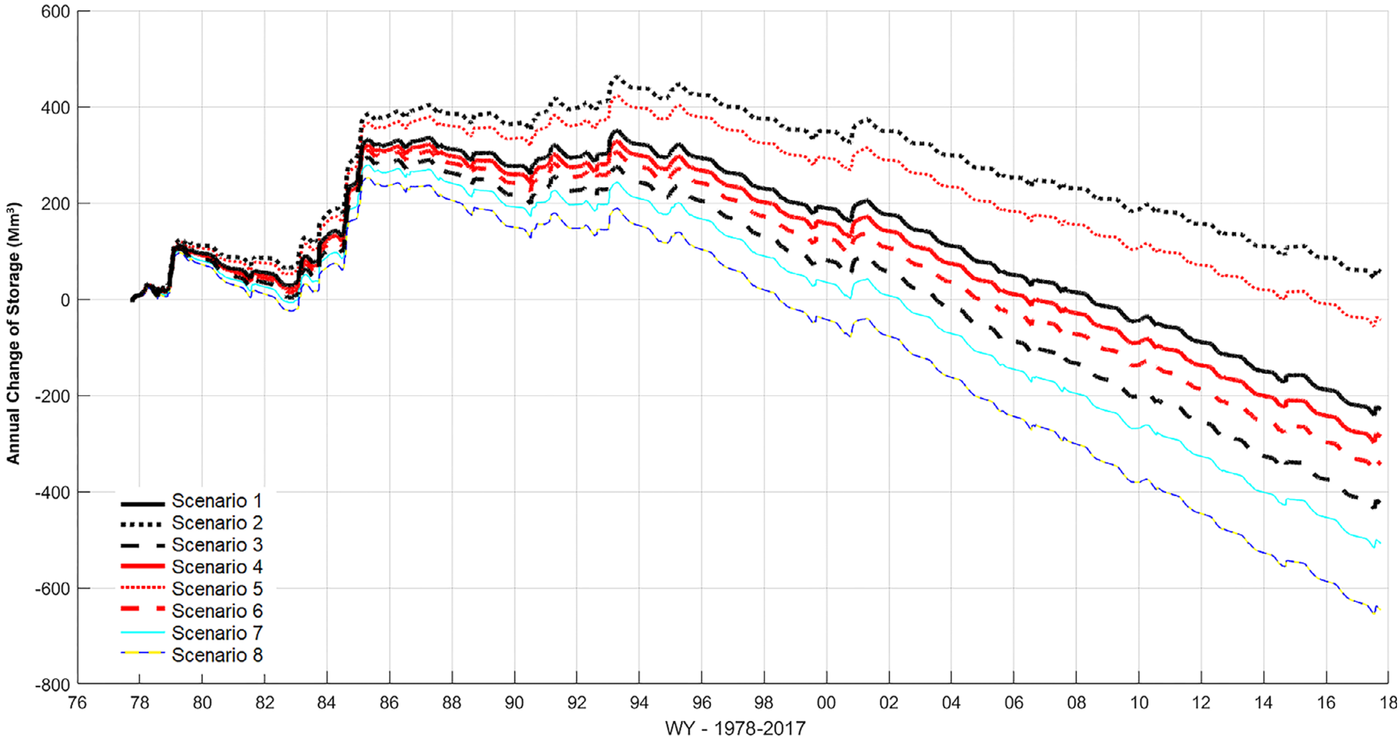

FIGURE 7. Cumulative water budget for 1978–2017 with different treated effluent discharge scenarios and 1997–2002 average pumping.

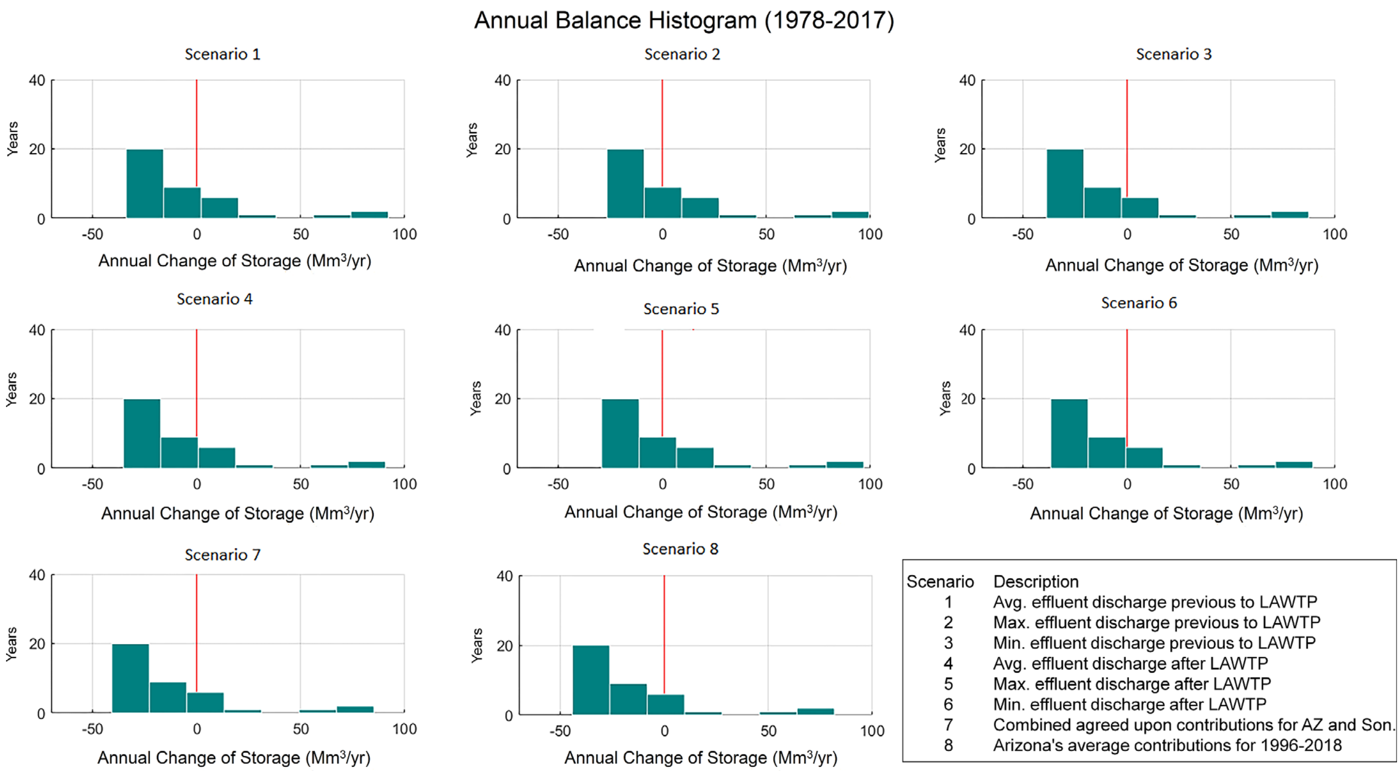

FIGURE 8. Histogram of the annual water balance during 1978–2017 with different treated effluent discharge scenarios and 1997–2002 average pumping.

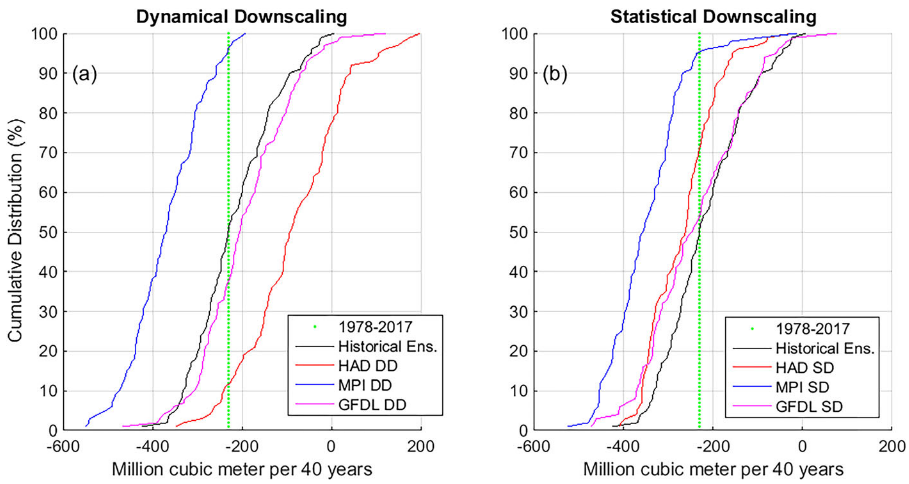

FIGURE 9. Cumulative distributions of projected 2020–2059 40-year cumulative water balance by the three global climate models dynamically (a) and statistically (b) downscaled simulations. The green line indicates as a reference the nominal case study using estimated SCR inflow for 1978–2017. The black line represents the cumulative distribution of the ensemble that represents the historic period.

Combined, the impact of both human and natural changes into the TSCA might be detrimental for water resources availability downstream of the NIWTP. These results are in agreement with previous studies that establish that variations in effluent discharge downstream of the binational NIWTP might reduce the perennial surface flow, vegetation habitat, property value, and groundwater recharge (Norman et al. 2013); and that groundwater recharge in the Upper Santa Cruz River is highly dependent on climate uncertainties and water management decisions (Shamir et al. 2015; Shamir 2017).

This water budget conceptual model improves the understanding of the impacts of variations in effluent discharge, groundwater demand, and surface water flows in the SCAMA, which is a requirement for the formulation of updated AWS rules that comply with the SCAMA management goals (ADWR 1999). Results from this conceptual water budget model can be used to identify the positive and negative change in aquifer storage under different policy-driven scenarios. The impact of these scenarios emphasizes the importance of adaptive management strategies and regulations based on scientific information that supports the conservation of surface and groundwater resources in this transboundary region.

This analysis sheds light on the current state of the TSCA with respect to groundwater availability and governance and recognizes the need for rules to achieve the SCAMA management goals. The predicted increase in groundwater pumping is mainly due to the projected increase in municipal demand (ADWR 2012a). In the context of groundwater management, results of this simulation can demonstrate the negative consequences of increasing groundwater pumping within the study region to land and water managers. The simulation can also demonstrate implications of this pumping increase for achieving the SCAMA management goals of maintaining safe-yield conditions and preventing local water tables from experiencing long-term declines, and the need of regulations that help to achieve these goals, such as the AWS rules.

Effluent discharge downstream of the binational NIWTP is an important source of recharge for the SCAMA. However, the discharge cannot be considered part of the 100-year AWS for the SCAMA in the U.S., at least not the portion that belongs to Mexico. One of the criteria for demonstrating AWS is to possess legal ownership of the water (A.A.C. R12-15-718) and Minute 227 and 276 indicate that Mexico reserves the right to reclaim the effluent from the NIWTP that is equivalent to the sewage inflow from Nogales, Sonora. We also recognize the importance of the binational effluent discharge for the health of the Santa Cruz River and note that current binational agreements do not discuss the perennial stretch that is fed by effluent discharge from the binational NIWTP. Future binational discussions over the amount and nature of the NIWTP effluent discharge should consider the TSCA as an interrelated binational system, reflect the groundwater and wastewater treatment demands of each nation, and the environmental water needs for the area, a topic beyond the scope of this paper.

CONCLUSIONS

Assessment of transboundary aquifers along the U.S.–Mexico border represents a challenge for land and water managers. Institutional asymmetries, lack of binational groundwater management agreements, and information disparities are some of the obstacles that interfere with the development of scientific research that improves the understanding of these shared aquifer systems. The TSCA is highly sensitive to climate uncertainties and water management decisions on both sides of the border. The groundwater dependence of Nogales, Sonora and Nogales, Arizona (Ambos Nogales), which are the main population centers within the region, adds additional pressure to decision makers that rely on available hydrologic studies for the development of groundwater management rules.

This study uses a simple conceptual water budget approach to assess the impacts of variations in groundwater demand, effluent discharge from the binational NIWTP, and Santa Cruz River natural flows in a portion of the TSCA located within the SCAMA. Mexican inputs to the aquifer system in the form of treated wastewater provide additional water volumes that help sustain the perennial reach located downstream of the binational NIWTP and provide a source of additional groundwater recharge for the SCAMA.

The SCAMA is an ADWR-regulated area with primary goals of maintaining safe-yield conditions and preventing local water tables from experiencing long-term declines (A.R.S. § 45-562C). The AWS rules, which require a 100-year water supply for new land subdivisions, are a key groundwater regulation. This impact assessment of the different components of the conceptual water budget model can guide water management decisions that consider the binational character of the aquifer and inform in the development of new AWS for the SCAMA.

Historically, wastewater from Ambos Nogales has been treated at the NIWTP in Rio Rico and discharged into the Santa Cruz River within the SCAMA. In 2012, LAWTP was built in Mexico to treat a proportion of the waste generated in Nogales, Sonora. The NIWTP and LAWTP were built in accordance to the Minutes approved by the IBWC with the objective of treating and reusing wastewater in Ambos Nogales and represent a case of successful binational collaboration between the U.S. and Mexico. LAWTP alleviates some of the Mexican wastewater contributions treated within U.S. territory. However, this study proves that variations in effluent discharge coupled with groundwater pumping contribute to groundwater deficits in the study region, whereas climate change scenarios project an uncertain future that ranges from severe long-term drying to positive wetting.

The analysis of the different facets of groundwater governance in the TSCA served to determine current gaps in binational agreements that have to do with the use and management of treated effluent from the NIWTP and the protection of the perennial stretch of the Santa Cruz River located downstream of the NIWTP. This approach can be used to analyze any transboundary aquifer within the U.S.–Mexico border and around the world. Even though the TAAP Cooperative Framework specifies that transboundary aquifer assessment should be solely for the purpose of expanding knowledge (IBWC 2009), the produced information will nevertheless benefit both countries. Future research directions for the TSCA within the TAAP Cooperative Framework include the development of a conceptual water balance model for the Mexican portion of the Santa Cruz River Basin and a hydrologic impact assessment. This future study will incorporate methodologies and lessons learned from this analysis downstream of the NIWTP, establishing its applicability within different regions.

ACKNOWLEDGMENTS

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APPENDIX 1

LIST OF ACRONYMS

Arizona Department of Water Resources	ADWR
Assured Water Supply	AWS
Comisión Nacional del Agua (Mexican National Water Comission)	CONAGUA
International Boundary and Water Commission	IBWC
Los Alisos Wastewater Treatment Plant	LAWTP
Nogales International Wastewater Treatment Plant	NIWTP
Organismo Operador Municipal de Agua Potable Alcantarillado y Saneamiento (Operating Municipal Agency of Potable Water, Sewage and Sanitation in Nogales)	OOMAPAS
Santa Cruz Active Management Area	SCAMA
Transboundary Santa Cruz Aquifer	TSCA

APPENDIX 2

WATER BUDGET MODEL COMPONENTS

In this appendix, we describe derivation of the various inflow and outflow aquifer fluxes that are included in the water budget model.

AQUIFER INFLOWS

Mountain-Front Recharge

This term describes the contribution to the aquifer from recharge along a mountain front. It is usually described as water that infiltrates into the zone of coarse alluvium that extends toward the piedmont at the mountain–basin interface. MFR is assumed to recharge the aquifer at a nearly uniform rate because of the inhibiting effect in the unsaturated zone. With lack of observed records, empirical equations to estimate MFR as a function of annual rainfall were developed. In this study, we adopted the long-term rate of 6.17 Mm^3/yr as estimated by Osterkamp (1973) and adopted by Nelson (2007) and ADWR (2012a).

Tributary Recharge

The main tributaries in the study area are Sonoita Creek, Agua Fria, and Peck Canyon. These ephemeral tributaries provide a steady recharge source to the central aquifer upstream of their confluence with the Santa Cruz River. The estimated recharge distributed over 14 tributaries within the study area varies between 8.14 and 10.30 Mm^3/yr Nelson (2007), Aldridge and Brown (1971), and Halpenny and Halpenny (1985). In this study, we used 9.22 Mm^3/yr, which is the average of the estimated range.

Santa Cruz River Streamflow

The surface flow in the study area is likely to be the water balance component with the largest range and largest inter-annual variability (Shamir et al. 2015). No streamflow measurements exist for the Santa Cruz River near the NIWTP, which is at the entrance to the study region. An upstream U.S. Geological Survey (USGS) active streamflow gauge near the Mexico–U.S. international border (USGS # 09480500, Santa Cruz River near Nogales) has provided a streamflow record since 1916. This station's drainage area is ~1,400 km^2, of which approximately 1,150 km^2 are in Mexico. Downstream of the USGS gauge, the ephemeral channel overlies the microbasins aquifer, which consists of a series of four relatively shallow, highly permeable and limited-storage-capacity alluvial aquifers that are bounded by the low-permeability Nogales Formation (Erwin 2007; Page et al. 2016). The microbasins extend along the river channel for about 25 km from the international border to the confluence with Nogales Wash near the NIWTP.

In previous studies, a modeling framework was developed to estimate the groundwater recharge in the microbasins given various water withdrawal criteria and water management strategies (Shamir et al. 2007a; Shamir et al. 2015; Shamir 2017; Shamir and Halper 2019). The aquifer recharge rate is the channel infiltration rate as in Erwin (2007), whereas recharge is dependent on the availability of free storage in the microbasins. The surface area of streamflow recharge is dependent on the width of the active channel, which is dynamically estimated as a function of the discharge rate.

This modeling framework uses the streamflow near the international border as input to estimate the streamflow at the outlet of each of the four microbasins and the flow at the Santa Cruz River near the NIWTP. The streamflow simulation used in our study was taken from Shamir (2017), in which the annual withdrawal rate from the microbasins aims for 6.17 Mm^3/yr as long as the average depth to water at each of the microbasins is below three meters. In addition to the model's assumptions with regard to the microbasins management and hydrological structure, the main assumption associated with the NIWTP inflow estimates is that no additional inflow is being contributed downstream of the international border.

The above-stated assumptions appear to hold well for the winter but not for the summer. A comparison was made for the 2000–2017 winter and summer natural flows at the Tubac gauge (USGS 09481740) to the Nogales gauge and the estimated flow at the NIWTP. The natural flow at Tubac was estimated by deducting the discharge of NIWTP-treated effluent from the measured flow at the Tubac gauge.

The estimated summer natural streamflow at Tubac is larger than both the flow measured at the Nogales gauge and the estimated flow at the NIWTP. The average natural summer flow at Tubac is ~2.5 times that at the Nogales gauge, during flow events that are smaller than 28.3 m^3/s. (1,000 ft^3/s). For the winter, the estimated flow at NIWTP aligns with the estimate of the natural flow at Tubac. Note, however, that during most winters within this period, the flow at both locations did not exceed 2.47 Mm^3/yr. Thus, for the derivation of estimated daily flow in the study area, we used the estimated flow at NIWTP for the winter (October–April) and the flow at the Nogales gauge for the summer (May–September). The summer flow at Nogales was scaled by 2.5 for daily flows that are smaller than 28.3 m^3/s.

Natural inflow can also be contributed from tributaries, namely Nogales Wash and Potrero Creek. These are relatively small tributaries in comparison to the Santa Cruz River, and we therefore assume that no significant surface flow from these tributaries is being contributed to the main stem of the Santa Cruz River. This assumption may have to be revisited, however, as the average annual flow during 2010–2017 at Nogales Wash in Nogales, Arizona is 8.34 Mm^3/yr (5.30 and 13.57 Mm^3/yr at minimum and maximum, respectively). During 2017, for example, the flow in Nogales Wash exceeded the flow at the Santa Cruz River near the U.S.–Mexico border (13.57 and 11.11 Mm^3/yr). However, as of today, we do not have sufficient information to account for the surface flow that enters the Santa Cruz River at the confluence with the Nogales Wash.

Incidental Agriculture Return Flow

The incidental agriculture return flow is estimated as 25% of the irrigated agriculture (ADWR 2012a). The average water withdrawal for agriculture in the study area for 1985–2015, as reported by the nonexempt wells, was 75% (63% and 88% at minimum and maximum, respectively). Projected overall agriculture water consumption for 2025 is estimated to be 56%–86% of the 2009 consumption (ADWR 2012b).

Subsurface Inflow

Nelson (2007) estimated a consistent subsurface influx to the study region from the Potrero area (4.32 Mm^3/yr), Nogales Wash (6.17 Mm^3/yr), microbasins (1.23 Mm^3/yr), and Sonoita Creek (0.62 Mm^3/yr). We revised these estimates to 3.70–4.93 Mm^3/yr from the combined Nogales Wash and Potrero areas, and ~4.93 Mm^3/yr from the microbasins and Sonoita Creek (Nelson and Hart, ADWR, June 2018, personal communication).

Effluent Discharge

Daily effluent discharge record from NIWTP for 2000–2017 that is available from IBWC was used to derive the eight different scenarios that were used in this study. Eight daily scenarios of possible treated effluent discharge into the Santa Cruz River were developed for this study. The first six scenarios represent the average, maximum, and minimum flow pre and postdevelopment of LAWTP. Scenario seven is equivalent to the U.S.–Mexico established contributions of 645 L/s (20.34 Mm^3/yr). This scenario was developed after several discussions with personnel from the Mexican section of the IBWC and OOMAPAS, which revealed that reducing their wastewater inflow to 434 L/s (13.69 Mm^3/yr) is a priority to reduce Mexican treatment costs and comply with Minute 276. This scenario also considers the 211 L/s (6.65 Mm^3/yr) corresponding to the U.S. agreed upon contributions for Nogales, Arizona. An enlargement to LAWTP to a capacity of 330 L/s and the proper maintenance of the pumping station will help to fulfill this objective at the cost of decreasing some of the Mexican NIWTP influent and therefore, the effluent discharged into the Santa Cruz River in the U.S. Scenario 8 is equal to only Arizona's average contributions (1996–2018), a case that considers a halt in Mexican inflows. Even though this might be considered an unrealistic scenario due to lack of infrastructure and resources availability, it is a possibility nevertheless, since Minute 226 and 276 establish that Mexico reserves the right to keep wastewater from Nogales, Sonora, within Mexican territory. Each of the eight scenarios is presented as a one year of daily flow that is repeated for the 40-year duration of the simulation.

AQUIFER OUTFLOWS

Evapotranspiration

Evapotranspiration along the Santa Cruz River corridor is a major yet relatively predictable outflow component of the region's water budget. A study by

ADWR (S. Masek, unpublished data) delineated the riparian coverage downstream of the NIWTP using 1954 and 1995 aerial photographs. The study identified seven vegetation groups with different annual ET water use. S. Masek (unpublished data) estimated the 1995 total ET rate (in the saturated and unsaturated zones) to be 18.50 Mm^3/yr. Nelson (2007) estimated the ET rate in the saturated zone for wet, average, and dry conditions to be 20.97, 19.12, and 17.27 Mm^3/yr, respectively. We note that although the amount of loss from the saturated zone is a substantial component of the water balance, the year-to-year (inter-annual) variability in potential ET is relatively small compared to that of some of the other water balance components. For example, an observed 1987–2002 annual reference ET (ET_o) record from a site in Tucson has a coefficient of variation of 0.05 (University of Arizona, The Arizona Meteorological Network. Accessed March 8, 2019, AZMET 2019, https://cals.arizona.edu/azmet/).

In this study, we assume an annual rate of 16.04, 18.50 and 20.97 Mm^3/yr for dry, medium and wet seasons, respectively, that is distributed monthly, as suggested by Gatewood et al. (1950) for riparian vegetation that consists of cottonwood and willow. The actual ET is highly dependent on the meteorological conditions (e.g. temperature, relative humidity, and wind), groundwater level, and riparian health. These are dynamic variables that are not being considered herein. Considerable changes in actual ET can potentially occur in the future due to declining water levels in the aquifer and changes in the riparian vegetation cover or health. Nevertheless, the water budget model does not consider potential changes in the actual ET. This omission may be warranted because of the perennial flow and high-water level in the aquifer caused by the persistent discharge from the NIWTP, which supports the riparian forest.

Groundwater Withdrawal

Water demand in the study area is mainly satisfied by groundwater withdrawal. The demand is dominated by agricultural consumption, which ranged from about 9.87 to 19.74 Mm^3/yr/YR during 1985–2009 (ADWR 2012a). Municipal water supplies, of which Rio Rico Utilities is the largest provider in this area, have gradually increased over time from about 1.23 Mm^3/yr/YR in 1995 to 3.70 Mm^3/yr in 2009 (ADWR 2012a). Nelson (2007), surveyed the 1997–2002 annual reports of the region's nonexempt wells to estimate an average annual withdrawal of 19.49 Mm^3/yr. Nonexempt wells are high capacity wells within the AMAs that must report their withdrawal to ADWR (A.R.S. § 45-2701(3)). Nonexempt wells in the SCAMA account for about 95% of the region's withdrawal. About 60% of the withdrawal takes place during the summer (May–September) and 40% in the winter (October–April). ADWR (2012b), projected that groundwater demand in the study area will gradually increase from ~20.97 Mm^3/yr in 2006 to ~28.37 Mm^3/yr in 2025. This predicted increase is mainly due to the expected increase in municipal demand.

Subsurface Outflow

Nelson (2007), stated that in general, during 1997–2002, the hydraulic heads and gradients remained relatively constant along the northern boundary of the study area. He estimated the underflow flowing north out of the SCAMA to be about 27.14 Mm^3/yr. This estimate is based on simulated underflow rates into the Tucson AMA (Mason and Bota 2006). A more recent estimate of the subsurface outflow is estimated to range between 20.97 and 33.30 Mm^3/yr (Hart and Nelson from ADWR, June 2018, personal communication).

Surface Outflow

Surface outflow on the Santa Cruz River was measured at the Amado streamflow gauge during 2004–2009. The average streamflow at Amado was ~13.57 Mm^3/yr. We note, however, that the available record from Amado dates from prior to the significant upgrade from a secondary to a tertiary treatment level at the NIWTP, which was completed in 2009. This upgrade resulted in reduction in nitrogen concentration in the treated effluent, which inhibits the formation of a biological seal on the channel's bed that in turn reduces stream infiltration (Treese et al. 2009). The streamflow at Amado after the NIWTP upgrade is likely to be lower because of the higher infiltration rate within the channel. Occasional 2013–2018 surveys by ADWR, in fact, reported no flow at Amado during February, May, August, and November.

In our model, the observed 2004–2009 record was adjusted to remove the baseflow that is not apparent after the upgrade. Following a visual analysis, to remove this baseflow, we considered only daily events that are larger than 0.42 m^3/s (15 ft^3/s). For the water budget model, we used the adjusted Amado flow for the average of winter and summer values. Additional daily surface outflow is being added during days with surface inflow that is higher than 141.58 m^3/s (5,000 ft^3/s), which is estimated as a maximum possible daily recharge.

For the water budget model simulations, we use the selected Santa Cruz River Nogales streamflow time series to categorize the summer and winter seasons in terciles of dry, medium and wet seasons. In addition to the ET that is modified based on the wetness categories as explained above, the mountain front recharge, groundwater tributaries, and surface outflow components are modified to increase or decrease their estimates by 50% for the wet and dry season, respectively. The selection to change by 50% is based on analysis of the terciles of the Nogales gauge seasonal streamflow.

LITERATURE CITED

ADWR. 1999. *Third Management Plan for Santa Cruz Active Management Area (2000–2010)*. Phoenix, Arizona: Arizona Department of Water Resources.

ADWR. 2012a. *DRAFT Demand and Supply Assessment*. Phoenix, Arizona: Arizona Department of Water Resources.

ADWR. 2012b. *Santa Cruz Active Management Area Water Demand and Supply Assessment: 1985–2025*. Phoenix, Arizona: Arizona Department of Water Resources.

ADWR. 2020. *AAWS Overview*. Phoenix, Arizona: Arizona Department of Water Resources.

Aldridge, B.N., and S.G. Brown. 1971. *Streamflow Losses in the Santa Cruz River and Groundwater Recharge, International Boundary to Cortaro, Arizona*. El Paso, Texas: International Boundary and Water Commission United States and Mexico.

Alley, W.M., and S.A. Leake. 2004. "The Journey from Safe Yield to Sustainability." *Ground Water* 42 (1): 12–16.

AZMET. 2019. *The Arizona Meteorological Network*. Tucson, AZ: The University of Arizona.

Callegary, J.B., S.B. Megdal, E.M. Tapia Villaseñor, J.D. Petersen-Perlman, I. Minjárez Sosa, R. Monreal, F. Gray, and F. Grijalva Noriega. 2018. "Findings and Lessons Learned from the Assessment of the Mexico-United States Transboundary San Pedro and Santa Cruz Aquifers: The Utility of Social Science in Applied Hydrologic Research." *Journal of Hydrology: Regional Studies* 20: 60–73. https://doi.org/10.1016/j.ejrh.2018.08.002.

Callegary, J.B., I. Minjarez, E.M. Tapia Villaseñor, P. dos Santos, R. Monreal Saavedra, F.J. Grijalva Noriega, C.A. Scott et al. 2016. *Binational Study of the Transboundary San Pedro Aquifer*. El Paso, TX: International Boundary and Water Commission.

CH2MHILL. 2009. *Nogales International Wastewater Treatment Plant Maximum Allowable Headworks Loading Development*. El Paso, TX: IBWC.

CONAGUA. 2007. *CONAGUA in Action*. México: Comisión Nacional del Agua.

CONAGUA. 2015. *Actualización de la disponibilidad media anual de agua en el acuífero Nogales (2650), Estado de Sonora*. Ciudad de México, México: Diario Oficial de la Federación.

CONAGUA. 2018. *Actualización de la disponibilidad media anual de agua en el acuífero Río Santa Cruz (2615) Estado de Sonora*. Ciudad de México, México: Diario Oficial de la Federación. .

DOF. 1917. *Constitución Política de los Estados Unidos Mexicanos*. Ciudad de México, México: Diario Oficial de la Federación.

DOF. 1992. *Ley de Aguas Nacionales*. Ciudad de México, México: Diario Oficial de la Federación.

Eckstein, G. 2011. "Managing Buried Treasure across Frontiers: The International Law of Transboundary Aquifers." *Water International* 36 (5): 573–83.

Eckstein, G., and F. Sindico. 2014. "The Law of Transboundary Aquifers: Many Ways of Going Forward, but Only One Way of Standing Still: The Law of Transboundary Aquifers." *Review of European, Comparative & International Environmental Law* 23 (1): 32–42. https://doi.org/10.1111/reel.12067.

Eden, S., S.B. Megdal, E. Shamir, K. Chief, and K. Mott Lacroix. 2016. "Opening the Black Box: Using a Hydrological Model to Link Stakeholder Engagement with Groundwater Management." *Water* 8 (5): 216. https://doi.org/10.3390/w8050216.

Erwin, G. 2007. *Groundwater Flow Model of the Santa Cruz Active Management Area Microbasins International Boundary to Nogales International Wastewater Treatment Plant Santa Cruz County, Arizona*. Modeling Report #15. Phoenix, Arizona: Arizona Department of Water Resources.

Gatewood, J.S., T.W. Robinson, B.R. Colby, J.D. Hem, and L.C. Halpenny. 1950. *Use of Water by Bottom-land Vegetation in Lower Safford Valley, Arizona*. Denver, Colorado: U.S. Geological Survey Water Supply Paper No. 1103.

Halpenny, L.C., and P.C. Halpenny. 1985. *Basic Data Report Well No. D(24-15) 08ada, Kino Springs, Santa Cruz County, Arizona*. Tucson, Arizona: Water Development Corporation.

Healy, R.W., T.C. Winter, J.W. LaBaugh, and O. Lehn Franke. 2007. *Water Budgets: Foundations for Effective Water-Resources and Environmental Management*. Reston, Colorado: U.S. Geological Survey Circular 1308, 90 p.

IBWC. 1958. *Minute No. 206 Joint Operation and Maintenance of the Nogales International Sanitation Project*. El Paso, TX: International Boundary and Water Commission.

IBWC. 1967. *Minute No. 227 Enlargement of the International Facilities for the Treatment of Nogales, Arizona and Nogales, Sonora Sewage*. El Paso, TX: International Boundary and Water Commission.

IBWC. 1988. *Minute No. 276 Conveyance, Treatment and Disposal of Sewage from Nogales, Arizona and Nogales, Sonora Exceeding the Capacities Alloted to the United States and Mexico at the Nogales International Sewage Treatment Plant Under Minute No. 227*. El Paso, TX: International Boundary and Water Commission.

IBWC. 1995. *Minute No. 294 Facilities Planning Program for the Solution of Border Sanitation Problems*. El Paso, TX: International Boundary and Water Commission.

IBWC. 2009. *Joint Report of the Principal Engineers Regarding the Joint Cooperative Process United States-Mexico for the Transboundary Aquifer Assessment Program*. El Paso, TX: International Boundary and Water Commission.

IDEAS. 2008. *Estudio Regional de Evaluación Hidrogeológica del Acuífero Santa Cruz, Municipios Santa Cruz y Nogales, Sonora*. Mexico: Investigación y Desarrollo de Acuíferos y Ambiente, S.A. de C.V. Hermosillo, Son.

Mason, D.A., and L. Bota. 2006. *Regional groundwater flow model of the Tucson Active Management Area, Arizona. Model Update and Calibration*. Phoenix, Arizona: Arizona Department of Water Resources.

Megdal, Sharon B. 2012. "Arizona Groundwater Management." *The Water Report* 104: 9–15.

Megdal, S.B. 2017. "The Cooperative Framework for the Transboundary Aquifer Assessment Program: A Model for Collaborative Transborder Studies." *Arizona Water Resource* 25: 1–2.

Megdal, S.B. 2019. *Reflections on the 10th Anniversary of the Transboundary Aquifer Assessment Program and the Importance of its Joint Cooperative Process*. Tucson, AZ: Water Resources Research Center.

Megdal, S.B., and J.D. Petersen-Perlman. 2018. "Groundwater Governance and Assessment in a Transboundary Setting." In *Lake Governance*, edited by V.I. Grover, 40–64. Boca Raton:

CRC Press, [2018]|Series: Water: Emerging Issues and Innovative Responses|"A Science Publishers Book." CRC Press.

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: 949–63.

Melillo, J.M., T.C. Richmond, and G.W. Yohe. 2014. *Climate Change Impacts in the United States: The Third National Climate Assessment*. Washington, D.C.: U.S. Global Change Research Program.

Meranza-Castillon, V., S.R. Hernandez, B. Ortiz-Navar, and R. Gutierrez-Gutierrez. 2017. "Impacto de la descarga de agua tratada en la cuenca los Alisos." *Revista de Ciencias Ambientales y Recursos Naturales* 3 (19): 18–28.

Milman, A., and C.A. Scott 2010. "Beneath the Surface: Intranational Institutions and Management of the United States — Mexico Transboundary Santa Cruz Aquifer." *Environment and Planning C: Government and Policy* 28 (3): 528–51. https://doi.org/10.1068/c0991.

Minjárez Sosa, J.I., R. Monreal Saavedra, M. Rangel Medina, F. Grijalva Noriega, J.A. Ochoa Granillo, E.M. Tapia Villaseñor, L. Ramírez Díaz et al. 2011. "*Actividades Hidrogeológicas En El Acuífero Río Santa Cruz, Estado de Sonora, Primera Etapa*." Hermosillo, México: Universidad de Sonora.

Mumme, S.P. 1980. "The US-Mexican Conflict over Transboundary Groundwaters: Some Institutional and Political Considerations." *Case Western Reserve Journal of International Law* 12: 505.

Nelson, K.M. 2007. *Groundwater Flow Model of the Santa Cruz Active Management Area along the Effluent-Dominated Santa Cruz River Santa Cruz and Pima Counties, Arizona*. Phoenix, AZ: Arizona Department of Water Resources.

Niraula, R., T. Meixner, and L.M. Norman. 2015. "Determining the Importance of Model Calibration for Forecasting Absolute/Relative Changes in Streamflow from LULC and Climate Changes." *Journal of Hydrology* 522: 439–51. https://doi.org/10.1016/j.jhydrol.2015.01.007.

Niraula, R., L.M. Norman, T. Meixner, and J.B. Callegary. 2012. "Multi-Gauge Calibration for Modeling the Semi-Arid Santa Cruz Watershed in Arizona-Mexico Border Area Using SWAT." *Air, Soil and Water Research* 5: ASWR.S9410. https://doi.org/10.4137/ASWR.S9410.

Norman, L.M. 2007. "United States-Mexican Border Watershed Assessment: Modeling Nonpoint Source Pollution in Ambos Nogales." *Journal of Borderlands Studies* 22 (1): 79–97. https://doi.org/10.1080/08865655.2007.9695670.

Norman, L.M., M. Feller, and D. Phillip Guertin. 2009. "Forecasting Urban Growth across the United States-Mexico Border." *Computers, Environment and Urban Systems* 33 (2): 150–59. https://doi.org/10.1016/j.compenvurbsys.2008.10.003.

Norman, L.M., H. Huth, L. Levick, I. Shea Burns, D. Phillip Guertin, F. Lara-Valencia, and D. Semmens. 2010a. "Flood Hazard Awareness and Hydrologic Modelling at Ambos Nogales, United States-Mexico Border: Flood Hazard Awareness and Hydrologic Modelling at Ambos Nogales." *Journal of Flood Risk Management* 3 (2): 151–65. https://doi.org/10.1111/j.1753-318X.2010.01066.x.

Norman, L.M., D. Phillip Guertin, and M. Feller. 2008. "A Coupled Model Approach to Reduce Nonpoint-Source Pollution Resulting from Predicted Urban Growth: A Case Study in the Ambos Nogales Watershed." *Urban Geography* 29 (5): 496–516. https://doi.org/10.2747/0272-3638.29.5.496.

Norman, L., N. Tallent-Halsell, W. Labiosa, M. Weber, A. McCoy, K. Hirschboeck, J. Callegary, C. Van Riper, and F. Gray. 2010b. "Developing an Ecosystem Services Online Decision Support Tool to Assess the Impacts of Climate Change and Urban Growth in the Santa Cruz Watershed; Where We Live, Work, and Play." *Sustainability* 2 (7): 2044–69. https://doi.org/10.3390/su2072044.

Norman, L., M. 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 (3): 852–74. https://doi.org/10.3390/w5030852.

Osterkamp, W.R. 1973. *Ground-Water Recharge in the Tucson Area, Arizona*. Tucson: AZGS.

Page, W.R., C.M. Menges, F. Gray, M.E. Berry, M.W. Bultman, M.A. Cosca, and D. Paco VanSistine. 2016. *Geologic Map of the Rio Rico and Nogales 7.5′ Quadrangles, Santa Cruz County, Arizona*. Reston: U.S. Geological Survey.

Peel, M.C., B.L. Finlayson, and T.A. McMahon. 2007. "Updated World Map of the Köppen-Geiger Climate Classification." *Hydrology and Earth System Sciences* 11 (5): 1633–44. https://doi.org/10.5194/hess-11-1633-2007.

Pierce, D.W., D.R. Cayan, and B.L. Thrasher. 2014. "Statistical Downscaling Using Localized Constructed Analogs (LOCA)." *Journal of Hydrometeorology* 15 (6): 2558–85. https://doi.org/10.1175/JHM-D-14-0082.1.

Pool, D. R. 2005. "IVariations in climate and ephemeral channel recharge in southeastern Arizona, United States." *Water Resources Research.* 41 (11).

Prichard, A.H., and C.A. Scott. 2014. "Interbasin Water Transfers at the US–Mexico Border City of Nogales, Sonora: Implications for Aquifers and Water Security." *International Journal of Water Resources Development* 30 (1): 135–51. https://doi.org/10.1080/07900627.2012.755597.

Quinn, N., S. Parrott, and M. Farley. 2016. *Conceptual Water Budget Analysis for Screening Agricultural and Wetland Water Management Projects*. Washington, D.C.: Bureau of Reclamation.

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 (2): 159–70. https://doi.org/10.3354/cr01061.

Shamir, E. 2017. "The Value and Skill of Seasonal Forecasts for Water Resources Management in the Upper Santa Cruz River Basin, Southern Arizona." *Journal of Arid Environments* 137: 35–45. https://doi.org/10.1016/j.jaridenv.2016.10.011.

Shamir, E., and E. Halper. 2019. *The Role of Downscaling Methodology in Projected Climate Change Impacts on Water Resources in Arid Environments*. Denver, CO: Research and Development Office, U.S. Department of Interior, Bureau of Reclamation.

Shamir, E., E. Halper, T. Modrick, K.P. Georgakakos, H.I. Chang, and T.M. Lahmers. 2019. "Statistical and Dynamical Downscaling Impact on Projected Hydrologic Assessment in Arid Environment: A Case Study from Bill Williams River Basin and Alamo Lake, Arizona." *Journal of Hydrology*. https://doi.org/10.1016/j.hydroa.2019.100019.

Shamir, E., S.B. Megdal, C. Carrillo, C.L. Castro, H.-I. Chang, K. Chief, F.E. Corkhill et al. 2015. "Climate Change and Water Resources Management in the Upper Santa Cruz River, Arizona." *Journal of Hydrology* 521: 18–33. https://doi.org/10.1016/j.jhydrol.2014.11.062.

Shamir, E., D.M. Meko, N.E. Graham, and K.P. Georgakakos. 2007a. "Hydrologic Model Framework for Water Resources Planning in the Santa Cruz River, Southern Arizona." *Journal of the American Water Resources Association* 43 (5): 1155–70. https://doi.org/10.1111/j.1752-1688.2007.00095.x.

Shamir, E., J. Wang, and K.P. Georgakakos. 2007b. "Probabilistic Streamflow Generation Model for Data Sparse Arid Watersheds." *Journal of the American Water Resources Association* 43 (5): 1142–54. https://doi.org/10.1111/j.1752-1688.2007.00094.x.

Sprouse, T.W., and A.I.V. Atondo. 2004. *Utilization of Wastewater on the United States-Mexico Border*. Tucson, Arizona: The University of Arizona.

Tapia Padilla, G. 2005. *Aplicación de modflow para la simulación hidrogeológica estacionaria de una porción de la Cuenca del río Santa Cruz, Sonora, México*. Hermosillo: Universidad de Sonora.

Treese, S., T. Meixner, and J.F. Hogan. 2009. "Clogging of an Effluent Dominated Semiarid River: A Conceptual Model of Stream-Aquifer Interactions." *Journal of the American Water Resources Association* 45 (4): 1047–62. https://doi.org/10.1111/j.1752-1688.2009.00346.x.

USIBWC. 2005. *Nogales International Wastewater Treatment Plant (NIWTP) Report on Pretreatment Activities*. El Paso, TX: International Boundary and Water Commission.

U.S. IBWC. n.d. "*The International Boundary and Water Commission - Its Mission, Organization and Procedures for Solution of Boundary and Water Problems*." El Paso, Texas: International Boundary and Water Commission.

Valles Delgado, V. 2014. *Saneamiento Fronterizo de Nogales, Sonora-Nogales, Arizona*. Chihuahua, Mexico: Comisión Internacional de Límites y Aguas (CILA).

Xu, C.Y., and V.P. Singh. 1998. "*A Review on Monthly Water Balance Models for Water Resources Investigations*. Dordrecht: Kluwer Academic Publisher.

Zhang, L., G.R. Walker, and W.R. Dawes. 2002. "Water Balance Modelling: Concepts and Applications." *ACIAR Monograph Series* 84: 31–47.