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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

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ABSTRACT

Study Region: This study region encompasses the Transboundary San Pedro and Santa Cruz aquifers which are shared between the states of Sonora (Mexico) and Arizona (US). Special regional considerations include a semi-arid climate, basin-fill aquifers with predominantly montane recharge areas, economic drivers in the mining, trade, and military sectors, groundwater-dependent cities with expanding cones of depression, interbasin groundwater transfers, ground- and surface-water contamination, and protected aquatic and riparian habitats that act as significant migration corridors for hundreds of species, including some that are threatened and endangered.

Study Focus: We focus on lessons learned from the hydrologic assessment of the Transboundary San Pedro and Santa Cruz aquifers. We conducted the work, in two phases: (1) laying the groundwork and (2) implementation. The "laying the groundwork" phase consisted of binational meetings with stakeholders and key actors (agencies and individuals), and the development of an understanding of the physical, institutional, historical, and socio-political context. This led to signing of the binational Transboundary Aquifer Assessment Program (TAAP) agreement in 2009 and detailed the process for cooperation and coordination in the assessment of shared aquifers. The implementation phase began with an agreement to proceed with the study of four "focus" aquifers (Santa Cruz, San Pedro, Mesilla (Conejos-Médanos in Mexico), and Hueco Bolson (Bolsón del Hueco in Mexico)) and development of associated technical teams. Though we do include a brief discussion of the lessons learned from the physical science portion of the study, the results have been described and published elsewhere. The bulk of the paper instead focuses on the findings and lessons learned from the integration of social-science perspectives into a largely physical-science based program, since there is a growing recognition of the need for this type of approach especially in the management and assessment of transboundary aquifers.

New Hydrological Insights for the Region: The Sonora-Arizona effort succeeded because both countries were adequately represented, and because of flexibility of skills and ability of teams comprising both university and government scientists. Teams included social and earth scientists. Including the social sciences was critical to research design and implementation, and to

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addressing the cultural, institutional, and socio-political contexts of transboundary aquifer assessment. Significant components of the continuing implementation phase include strategic planning, data compilation and analysis, cross-border integration of datasets, geophysical and geochemical surveys, and internal, peer, and stakeholder engagement.

1. Introduction

Transboundary aquifers represent a source of water of growing importance globally for reasons of increasing water use scarcity and contamination, scarcity caused by growth in population, agriculture, industry, climate change, and drought. The resulting need requires the development of agreements to share and manage transboundary waters. Water governance, of which sharing and management are components, can present a number of challenges (Foster et al., 2010; Varady et al., 2016). There is also recognition that without basic hydrologic information, aquifer management and water resource planning would be difficult. Water quality can be impaired as a result of scarcity, resulting in impacts to human health and economic activities through declines in agricultural production, loss of ecosystem services, and the costs of water treatment and remediation. Those factors may be exacerbated by climate change and drought cycles, both of which are likely to affect the southwest United States (Garfin et al., 2013) as concentrations of salts and contaminants rise in water supplies.

Assessing a transboundary aquifer involves more than simply the study of the physical aspects of the aquifer and its environment. Where waters straddle a political boundary, the complexity of assessment and management increases. By assessment we mean the development of information, through both data collection and analysis, which is conducted in an impartial and reproducible way. Factors such as politics, policy, differing legal frameworks, resources (political, economic, and/or military), institutional capacity, interstate relations and history, and cultural and linguistic differences all come into play (Blomquist and Ingram, 2003; Norman and Bakker, 2005). Therefore, the usual approaches employed by hydrologists to understand cooperator/client needs, develop workplans, and carry out studies are insufficient, and the required skill sets exceed the abilities and training of most hydrologists. Currently, a range of multidisciplinary approaches encompassing the fields of law and the physical and social sciences are being applied to the study of transboundary aquifers. Successful approaches to initiate cooperation over transboundary waters include respecting the autonomies of participating countries, creating networks of scientists from participating countries, consulting diverse groups of stakeholders, and allowing for each participating country to have ownership of specific cooperative activities (Petersen-Perlman and Wolf, 2015), thereby mitigating the perceived risk countries face by entering into cooperative frameworks (Subramanian et al., 2012). Such approaches include aquifer assessments and classification schemes designed to support developing systems of international law, governance, and management (Alley, 2013; Callegary et al., 2016; Eckstein and Eckstein, 2005; Eden et al., 2016; Petrossian et al., 2017; Sanchez et al., 2016; Shamir et al., 2015). They also include studies of cooperation-conflict scenarios embodying a nuanced recognition that cooperation and cooperation commonly exist side by side (Conti, 2014; Delli-Priscoli, 1994; Wolf, 2008; Zeitoun and Mirumachi, 2008).

Groundwater shared between the US and Mexico is no exception to these complexities and challenges, and the two countries share a number of hydrological basins crossed by the international boundary. In the early 2000s, US agencies and institutions, including the Water Resources Research Institutes (WRRIs) of Texas, New Mexico, and Arizona, cooperated in a series of binational discussions and meetings in response to the urgent need to study shared groundwater along the Mexico-US border. As a result, the US Congress authorized Public Law 109–448, the United States-Mexico Transboundary Aquifer Assessment Act (TAA Act), in December 22, 2006 (Alley, 2013), authorizing funding of $50 million USD over a ten-year period. The TAA Act created the ground rules for the US team with regard to which institutions would be involved and consulted, and with regard to US overall goals:

1 “develop and implement an integrated scientific approach to identify and assess priority transboundary aquifers”
2 “consider the expansion or modification of existing agreements, as appropriate, between the United States Geological Survey, the Participating States, the Water Resources Research Institutes, and appropriate authorities in the United States and Mexico.”

The Act signaled the US's interest in binational studies and authorized US involvement. Consultation with and a request for involvement from Mexico were the next steps. Thus began the process, described in this paper, of negotiation, engagement, and mutual learning that resulted in a formal agreement between the two countries in 2009 to allow the study of transboundary aquifers (IBWC, 2009). Four transboundary aquifers were chosen for initial study: the San Pedro and Santa Cruz (shared between Sonora (Mexico) and Arizona (US)), Mesilla (shared among Chihuahua (Mexico), New Mexico (US) and Texas (US)), and the Hueco Bolson (Chihuahua and Texas). We focus on the Transboundary San Pedro Aquifer and the Transboundary Santa Cruz Aquifer System (TSPA and TSCAS respectively), where continual binational work has taken place from 2007 to the present. The studies described here are limited to subwatersheds of larger geologic basins straddling the Mexico-US border.

The objectives of this paper are to describe the multidisciplinary approach, involving a combination of social and physical sciences, and university and government institutions and scientists, that was used for the study of the TSPA and TSCAS. We describe the process of laying the groundwork, specifically negotiation, engagement, and mutual learning leading to agreement between the two countries. We document the results of combined application of physical and social sciences to assess priority transboundary aquifers. Finally, we summarize our successes and failures, and propose opportunities for improvement.

1.1. Background

1.1.1. What do international law and policy have to do with hydrology?

The hydrologic assessment of transboundary aquifers is just one piece within the larger arena of international law, policy, and management. Development of international legal and policy frameworks for the study of transboundary aquifers began long before the current study, providing a rich history that informed our approach. International discussions between the US and Mexico began in the 1990s and continuing to the present. These discussions, formalized or published in policy briefs, reports, and journal articles, attempted to recognize, describe, and formulate policy and legal frameworks in terms of the economic value of groundwater (Agarwal et al., 2000), and more recently, to situate groundwater within the water-food-energy-climate-ecosystem nexus (Bazilian et al., 2011; Berardy and Chester, 2017; de Strasser et al., 2016; Dodds and Bartram, 2016; Ringler et al., 2013). As an example, the 9th International Symposium on Managed Aquifer Recharge (ISMAR9), held in June 2016 in Mexico City, focused on increasing groundwater's visibility and promoting sustainable groundwater management. The symposium resulted in six policy directives (ISMAR9, 2016). The first directive called for recognizing aquifers and groundwater as "critically important, finite, valuable and vulnerable resources." Next, the symposium called for halting the chronic depletion of aquifers across the globe. The third directive called for information on groundwater to be shared widely, citing the uniqueness of all aquifer systems and the need for these systems to be well-understood. Further directives called for sustainable management and protection of groundwater using integrated water resources management principles (Agarwal et al., 2000) and advocated increased managed aquifer recharge. Finally, the sixth directive addressed the need for collaboration, strong stakeholder participation, and community engagement in effective groundwater management.

The principles outlined in the ISMAR9 Directives reflect the 2008 United Nations Draft Articles on the Law of Transboundary Aquifers (Draft Articles). The Draft Articles are arguably the most significant effort to date for developing any international regulatory system for transboundary aquifer systems (Eckstein, 2011). The 19 Draft Articles are modeled on the 1997 United Nations Convention on the Law of the Non-Navigational Uses of Transboundary Watercourses (UN Convention), and include rules for equitable utilization, obligation to cause no significant harm, and promotion of international and technical cooperation (Eckstein, 2011). The ratification of the Draft Articles will be included once again in the provisional agenda of the seventy-fourth session of the UN General Assembly in 2019 (UNGA, 2016).

The Draft Articles encourage nations to enter into bilateral or regional agreements, but to date only a handful of such formal agreements over transboundary aquifers have been formalized. The transboundary waters task force of UN-Water crafted seven pillars that are considered necessary for reliable, long- lasting, and sustainable transboundary water cooperation (UNGA, 2010). The text of the first pillar recommends a sound legal framework. UN-Water called for agreements to be concrete and to aim for cooperative institutional agreements, with enforcement mechanisms, on the protection of water resources and related ecosystems. The second pillar proposes appropriate institutional structures with strong capacities at national, international, and regional scales. Third, transboundary water development and management should feature long-term and contingency planning to make vulnerable systems more resilient. The fourth pillar calls for data exchange, joint monitoring, and assessment of shared waters. The fifth pillar recommends public participation with the aims of enhancing transparency, creating ownership, and working toward agreement on policies and management decisions. Sixth, the panel calls for countries sharing river basins to share benefits from the rivers fairly and justly compensate those who suffer losses. The seventh and final pillar states that in order to accomplish everything listed above, appropriate financing is necessary (UNGA, 2010).

Taken together, the directives, Draft Articles, and pillars mentioned in the preceding paragraphs apply directly to projects such as ours by affirming the importance of groundwater, the need for better information, and the need for collaboration to obtain it. They also raise the visibility of groundwater internationally and provide a set of guidelines for countries seeking to develop and prioritize objectives and behaviors related to transboundary groundwater issues.

1.2. Site descriptions

Although the San Pedro River riparian corridor has received considerable international attention, the TSPA, along with the TSCAS, only began to receive attention late in the last decade. The 2009 update to the International Groundwater Resources Assessment Center's Transboundary Aquifers or the World Map featured both aquifers (IGRAC, 2009). UNESCO's Internationally Shared Aquifer Resource Management (ISARM) program listed the aquifers as part of the inventory listed in the ISARM of the Americas inventory.

1.2.1. Transboundary San Pedro Aquifer

The TSPA is of critical interest because of the high ecological value of the riparian ecosystem sustained by the San Pedro River (CEC, 1999; Gungle et al., 2016), and the need for groundwater to sustain the river, existing communities, and continuing development. The TSPA and its watershed make up one of the most studied hydrologic systems in the region because of their economic, historical, and environmental characteristics (Richter et al., 2014). Previous studies include topics ranging from geophysics and hydrology to biology and ecosystem services (Anning and Leenhouts, 2010; Bagstad et al., 2013, 2005; Callegary et al., 2007; Gungle et al., 2016; Lite and Stromberg, 2005; Moran et al., 2008; Pool and Dickinson, 2007; Stewart et al., 2012). The economic drivers differ on each side of the border with military and tourism in Arizona and mining in Sonora as the lead industries. The copper deposit at Cananea is responsible for about 40% of copper production in Mexico (Jiménez, 2014). With over 350 species of birds, and over 80 species of mammals, the riparian forest and flanking areas along the San Pedro River have been recognized as a critical North

American biodiversity hotspot and critical migratory corridor (CEC, 1999) and several projects have been initiated to maintain baseflow in the river using managed aquifer recharge (Richter et al., 2014) (Fig. 1).

1.2.2. Transboundary Santa Cruz AAquifer System

In the TSCAS, the major economic drivers include commerce at the international border, and a significant manufacturing sector on the Mexican side of the border. About 100 manufacturing plants, employing over 34,000 people, were registered in Nogales, Sonora in 2014 (Pavlakovich-Kochi, 2014), and the plants can have negative environmental impacts if their discharges do not meet water quality standards. The TSCAS is the main source of water for the twin cities of Nogales, Sonora and Nogales, Arizona, which have a combined population of about 250,000 (CONAGUA, 2015c; Erwin, 2007; INEGI, 2017; Scott et al., 2012; USCB, 2017). In addition to obtaining groundwater from the Santa Cruz Aquifer, Nogales, Sonora also uses groundwater from the Nogales and Los Alisos aquifers, and Nogales, Arizona maintains a wellfield to the west of the city (CONAGUA, 2015b; Nelson, 2007; Scott et al., 2012). Municipal water providers struggle to meet the demands due strongly seasonally variable groundwater levels in wells near the Santa Cruz River (Prichard and Scott, 2014). The Nogales International Wastewater Treatment Plant, situated in Arizona, treats effluent from both cities with about 80% originating in Nogales, Sonora (IBWC, 2017). The effluent is discharged into the Santa Cruz River where it helps to sustain riparian habitat and stabilize groundwater levels for up to 15 km downstream of the facility. Acknowledging the unique set of conditions present in the portion of the TSCAS near the US-Mexico border, the Arizona Department of Water Resources (ADWR) created the Santa Cruz Active Management Area (AMA) in 1994 (ADWR, 2010). AMAs are areas in which ADWR regulates the use of groundwater in accordance with the 1980 Arizona Groundwater Code (ADWR, 2017).

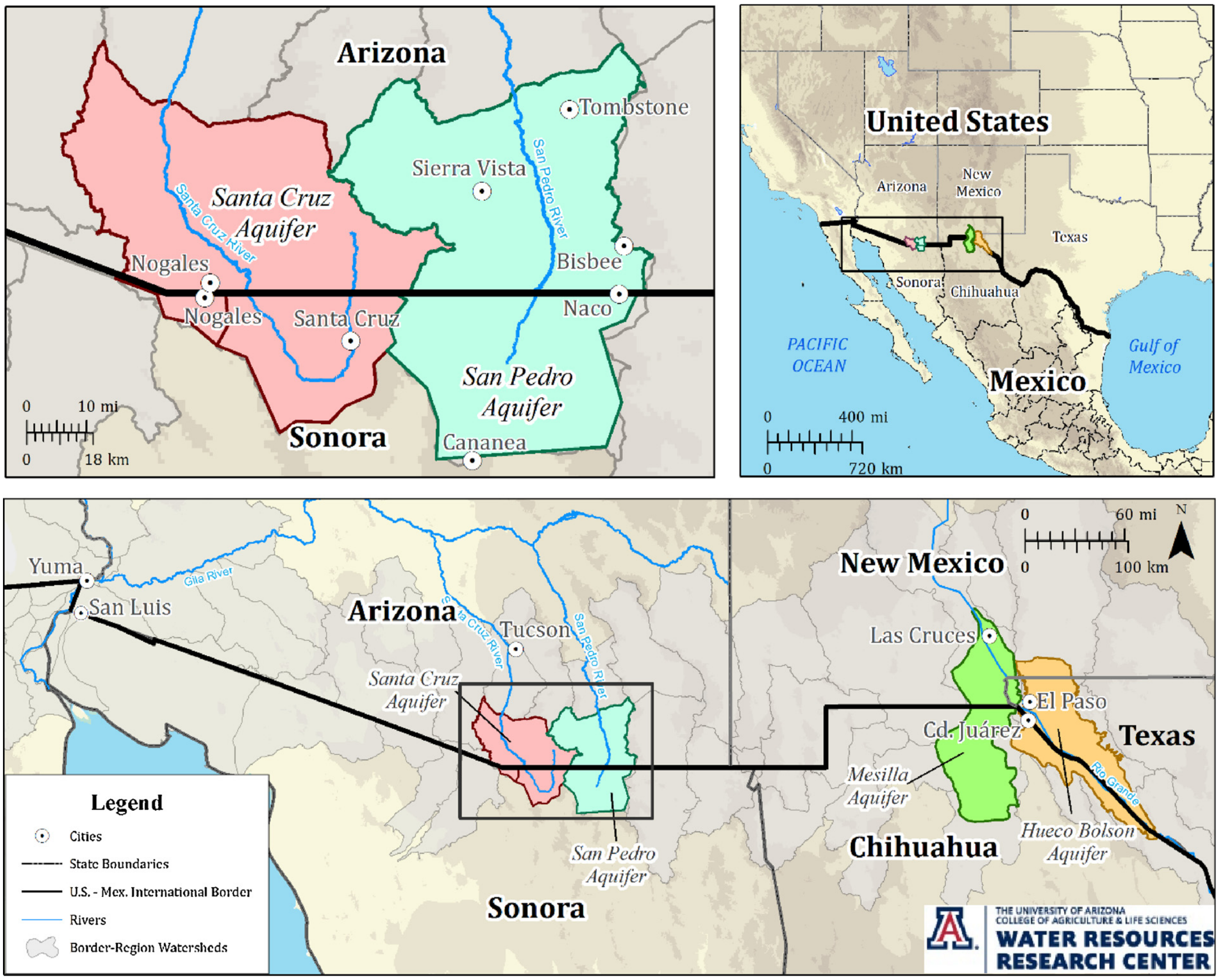

Fig. 1. Focus transboundary aquifers along the US-Mexico Border. The Santa Cruz and San Pedro aquifers are the focus of this study.

2. Materials and methods

2.1. Laying the groundwork

By “laying the groundwork”, we mean those factors or actions required at the outset of the project in order to move forward with the physically-based study of the aquifers. Some of these factors were anticipated, and others were added along the way as the need became evident. Some were learned in hindsight. In typical groundwater assessments it is unusual to consider some factors investigated for this study. These include **institutional, economic, historical, and socio-political factors**, but these affect who is involved, what language(s) and methods of communications are used, ease of travel, and availability of funding. They can also inform, somewhat unexpectedly, preliminary conceptual models and task development with respect to subjects such as land use/land cover, water budgets, water quality, and units of measurement.

Methods and results used to assess **governance and legal and institutional frameworks** are documented in Megdal and Scott (2011); Megdal et al. (2010) and Scott et al. (2010). Milman and Scott (2010) determined the key aspects that influence water management in transboundary settings. Understanding these factors is critical to understanding the mechanisms for supporting the work on a prospective as well as retrospective basis, as changing policy and management environments and funding cycles have direct bearing on the workflow.

Development of a Binational Agreement, though not initially foreseen as a requirement for the binational work, was one of the principle activities of the first several years of the project. The TAA legislation in the US did not involve an agreement with Mexico, but institutional frameworks required binational consultation on water issues to occur through the International Boundary and Water Commission (IBWC). The IBWC (la Comisión Internacional de Límites y Aguas, or CILA, in Mexico) is one organization with two sections, a Mexican and a U.S. section. It is a branch of the State Department in the U.S. and of the Secretaría de Relaciones Exteriores in Mexico. Following IBWC protocols, in order for progress to be made on studies, a binational agreement was needed. The IBWC and the Mexican National Water Commission (Comisión Nacional del Agua or CONAGUA) were key players in the development of the agreement that established the binational TAAP. In the US, representatives of the university-based Water Resources Research Institutes (WRRIs) were key negotiators. The WRRIs are federally authorized, with a long-standing working relationship with and funding from the US Geological Survey (USGS).

Identification of Team Members was constrained by law, custom and regulation in each country. In part, it involved the selection and inclusion of agencies and individuals deemed necessary, given the resources and personnel available, to carry out the functions of the project. The team member selection process evolved between 2007 and about 2009 to conform more closely with legal and regulatory requirements in both countries. The approach of the US part of the team was constrained by the language of the TAA Act and its requirement of the “maximum extent practicable” for cooperation and the development of relationships with organizations in Mexico. The TAA Act required the participation of the USGS and the WRRIs. In Mexico selection of member agencies was made with regard to federal requirements for consultation and work with particular agencies, namely CONAGUA and IBWC. These agencies then contracted as needed with other institutions such as the University of Sonora and the Mexican Geological Service.

Communication and stakeholder engagement were key to the success of the project. A flexible approach amenable to the changing demands of the project prevented detailed long-term planning at the outset. However, approaches to different levels of communication — internal communication, peer-to-peer, and with stakeholders — were worked out over time. Various tools and techniques were used including development of bilingual web products, fact sheets, binational workshops, and field trips. Like technical studies, engagement efforts require resources, which were intermittent. A broad set of stakeholders was involved in early assessment scoping efforts; a successful workshop organized by the University of Arizona’s Water Resources Research Center (WRRC - the primary institution on the team with social-science expertise). The workshop involved a long list of stakeholders from both countries and both aquifers and was held in late 2009. After a long period (approximately 2011–2016) of focusing on the physical science portion of the transboundary studies, new efforts by the WRRC to disseminate and explore the findings and engage a broader set of stakeholders are underway.

The development of an approach to **planning and decision making** was not a linear process. It began simply, eventually evolving into agreements and workplans. Contractual agreements were used to formalize expectations whether tasks arose from a funding agreement, or from an accord formalizing a working relationship between two entities with representation on the binational team. Formal agreements were used to clarify the roles of institutions, committees, working groups, and personnel, and to guide future work.

2.2. Developing physical context: Climate, hydrology land cover, vegetation, soils, and geology

The development of an understanding of the physical context required information on climate, land cover, hydrology, vegetation, soils, and geology. A literature review was conducted for each aquifer (Vandervoet et al., 2013). One of the main goals was to develop a binational database with the goal, as specified by the “Joint Report of the Principal Engineers Regarding the Joint Cooperative Process United State-Mexico for the Transboundary Aquifer Assessment Program” (hereafter referred to as the Joint Report), that metadata be developed and that the database be housed and served by the IBWC. For the TSPA, data and existing literature on the aforementioned topics were summarized in Callegary et al. (2016). For the TSCAS, a binational report using the same approach has been drafted and is in review. Field work included geophysical, geochemical, and hydrological studies (Callegary et al., 2016, 2013; Minjárez Sosa et al., 2011a; Stewart et al., 2012). Modeling included chemical transport modeling (McAndrew, 2011) and assessment of aquifer vulnerability to contamination (Lincicome, 2011). When priorities and funding allowed, field work and modeling were conducted in both the US and Mexico using standard approaches. The results and analysis were published as abstracts, graduate theses, journal articles, and reports (Alley, 2013; Stewart, 2014; Callegary et al., 2017; Megdal, 2017; Minjárez et al., 2017; Callegary et al., 2018). Geologic field work is ongoing and includes geologic mapping, and geophysical and hydrochemical surveys. Hydrochemical surveys were carried out by the Universidad de Sonora (Minjárez Sosa et al., 2011a,b). Hydrochemical data for the US were taken from the ADWR and USGS databases and water quality reports and the obtained information allowed us to identify groundwater families in the binational context.

3. Results and discussion

3.1. Laying the groundwork

Understanding the context when approaching the study of transboundary aquifers is critical to project success. Context includes the economic, historical, and socio-political setting in which the study is to occur. It also includes legal and institutional frameworks. Lack of knowledge can hinder progress or even shut down a project.

3.1.1. Economic, historical, and socio-political setting

In Mexico, primary authority for management of water resources emanates from the federal government to the states and municipalities. In the United States, primary authority rests with the states except in cases of interstate surface waters. Binational waters are not currently jointly managed by the two countries except in cases where treaties have been negotiated such as for the Rio Grande and Colorado rivers. The 1944 Water Treaty serves as the main reference for binational water management in the US and Mexico (Michel, 2003). It establishes the distribution of water on the Colorado and Tijuana Rivers, and the Rio Grande. However, it does not address *groundwater* management (Milanes Murcia, 2017). The only attempt to include groundwater management in the border region is Minute 242, which limits the groundwater extractions from the Yuma aquifer, located within the states of Arizona and Sonora (Sanchez and Eckstein, 2017; Mumme, 2000). Minutes are not amendments to the Treaty, but are decisions made by the IBWC and are used to carry out the provisions of the 1944 Treaty. Guidelines and agreements providing jurisdiction or establishing a process for binational consultation include the La Paz Agreement of 1983 and the Integral Environmental Plan for the US-Mexico border of 1992. An awareness of this shared history, as well as current events and political realities, was critical when approaching the binational work.

3.1.2. Legal framework, institutional setting

Political, resource management, and decision-making authority tend to be more centralized in Mexico than in the US (Megdal et al., 2010; Megdal and Scott, 2011). In Mexico, much of the authority to regulate water lies with CONAGUA, and in the case of binational water, some of that authority lies with the IBWC. In the US, depending on the issue, water management jurisdiction varies. It may require the participation of multiple institutions such as state water and environment departments, and in the case of interstate waters and contamination, other agencies may need to be involved, such as the EPA. With respect to water research, any of the aforementioned institutions may be involved, but also universities and the USGS. The resulting institutional asymmetries required each group to learn and adjust to the functions and procedures of the partner institutions, such as communication protocols, rules, and customs. Questions that needed to be answered included: How is communication initiated? What is the chain of communication? What permission is needed and in what situations is informal communication acceptable? Decisions were also required on procedures for approval of proposals and decisions, review of draft manuscripts, and data exchange. IBWC protocols provided a starting point for communication and distinguishing between formal and informal exchanges (Fig. 2).

3.1.3. Development of a binational agreement

Owing to its expertise in managing treaty obligations and Mexican policies regarding transboundary waters, negotiations through the IBWC were central to formalizing cooperation and establishing the nature of the cooperation. The discussions, meetings, joint

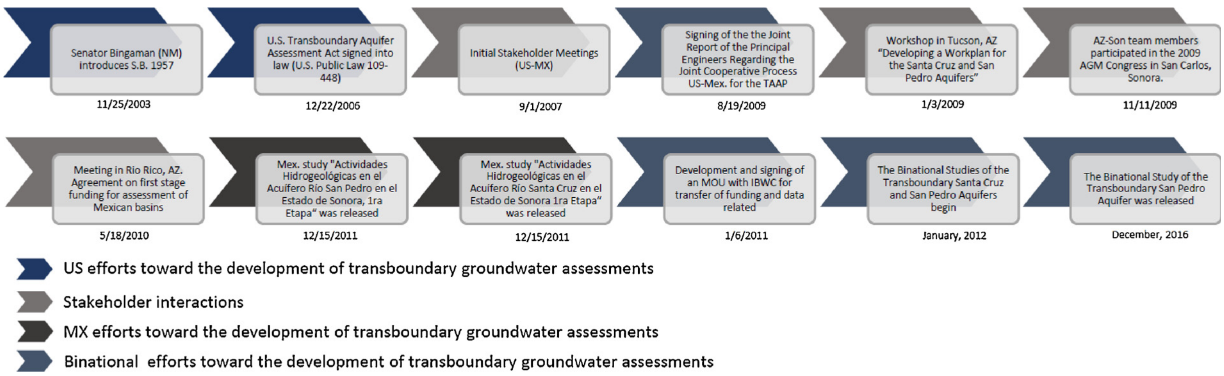

Fig. 2. Timeline of significant milestones in development and progress of the TAAP-Arizona-Sonora effort.

presentations at a conferences, and legislation ultimately led to the 2009 signing of the Joint Report. The Joint Report established the framework for US-Mexico coordination and dialogue to implement transboundary aquifer studies (Megdal, 2017). The document clarifies program details such as background, roles, responsibilities, funding, relevance of the international water treaties, and the use of information collected or compiled as part of the program. Four priority aquifers (Santa Cruz, San Pedro, Mesilla, and Hueco Bolson) were agreed upon by the parties involved, which included the IBWC, the CONAGUA, the USGS, UNISON, and the WRRIs at New Mexico State University, Texas A&M and the University of Arizona. Approval was later given to add the Nogales aquifer, classified as a separate aquifer in Mexico, in recognition of the fact that it is hydraulically connected via both surface and groundwater to the Santa Cruz aquifer in the US.

By agreement, the Transboundary Aquifer Assessment Program (TAAP) has focused on assessment and not management. Indeed, a clause of the Joint Report reads: "The information generated from these projects is solely for the purpose of expanding knowledge of the aquifers and should not be used by one country to require that the other country modify its water management and use." Nevertheless, the TAAP furthers two important components of the UN 2008 Draft Articles on the Law of Transboundary Aquifers. The first is Article 7, §2, the General Obligation to Cooperate, which calls for establishment of joint mechanisms of cooperation. The second is Article 8, §2 on the regular exchange of data and information: "Where knowledge about the nature and extent of a transboundary aquifer or aquifer system is inadequate, aquifer States…shall take such action individually or jointly and, where appropriate, together with or through international organizations."(Table 1).

3.1.4. Available resources: technical and financial

Financial resources were provided by each country. US funding was divided equally, as required by the TAA Act, among the WRRIs and the USGS Water Science Centers in Texas, New Mexico, and Arizona. With respect to the San Pedro, Santa Cruz, and Nogales Aquifers, the WRRC (the WRRI based at the University of Arizona) and IBWC contributed additional funding. In Mexico, funds were provided by CONAGUA to the Mexican section of the IBWC and, thence, to the UNISON. At times, funding in availability in one country would lag behind funding in the other, resulting in differences in the amount and type of work occurring in each country. No restrictions were imposed on funding coming from additional sources. This, and the fact that the TAAP is a partnership of universities and government in two countries, all with different sources and timing of funding, added flexibility that allowed at least a minimal level of work even in years with low or no funding. Technical resources were available through a variety of institutions. In Mexico, CONAGUA often obtains technical expertise under contract with universities.

3.1.5. Identification of team members

One of the initial challenges was determining which parties should come to the table, and which were required by government laws and regulations. Team composition evolved substantially over a period of several years, in part because the US team worked initially under the assumption that there would be no constraints as to which agencies and institutions they could work with in Mexico. A variety of institutions in the US had considerable experience working with Mexican partner institutions. In the US, the USGS and the WRRIs located in the three states designated in the TAA Act are core team members, and have determined which other partners were invited to consult or participate. In Arizona, the Arizona Department of Water Resources, the Upper San Pedro Partnership, and the City of Nogales were consulted. The binational IBWC has played a key role in the binational team because of its centrality in the study and management of binational water as well as the fact that it is part of the state department of both countries. In addition, Mexico's policy requires that all border water issues be handled through IBWC. Also in Mexico, CONAGUA has played the role of chief policy and funding coordinator for water studies, while UNISON was contracted because of its technical expertise.

Scientific assessment of the aquifers was carried out by a team under the guidance of a Binational Technical Group and a Working Group, as stipulated by the Joint Report. The Binational Technical Group's role was to oversee the development of work plans and goals. The Working Group was responsible for carrying out individual tasks and documenting progress via reports, journal articles, and factsheets. Given that some critical TAAP personnel are political appointees and therefore subject to election cycles, there has been remarkable stability of team membership. This has allowed for the building of mutual trust, and the flexibility required for working within each country's institutional environment (Wilder et al., 2010). Geophysical surveys, aquifer tests, and water quality sampling were carried out by faculty and students from UNISON through contract with IBWC. In the US, field activities were carried out by the scientists from the USGS and faculty and students from the University of Arizona.

Table 1
Selected guiding principles from the Joint Report (IBWC, 2009).

	Guiding Principles from the Joint Report
1	The activities described under this agreement should be beneficial to both countries.
2	The aquifers to be jointly studied, as well as the scope of the studies or activities to be done on each aquifer, should be agreed upon within the framework of the IBWC.
3	The activities should respect the legal framework and jurisdictional requirements of each country.
4	No provision set forth in this agreement will limit what either country can do independently in its own territory.
5	No part of this agreement may contravene what has been stipulated in the Boundary and Water Treaties between the two countries.
6	The information generated from these projects is solely for the purpose of expanding knowledge of the aquifers and should not be used by one country to require that the other country modify its water management and use.

3.1.6. Planning and decision-making

Generally binational priorities were developed jointly; however, each country, in accordance with the Joint Report, can carry out work within its own borders without needing to consult the other. Thus, some TAAP-related studies were not binational, though they were designed to contribute to the overall objectives of the TAAP. Binational forums addressing the Arizona-Sonora aquifers in 2009, and the four focus aquifers in 2016 resulted in the development of Strategic Plans outlining priorities and tasks over multi-year periods. Annual tactical plans, instituted in 2016, outline the implementation of the Strategic Plans year by year, taking account of current realities relating to funding, resources, personnel, any new challenges, and progress to date. Tactical workplans were used to outline and agree upon short term goals, tasks, budgets, and timelines usually expected to last one to three years. Strategic workplans were used to outline long-term vision and estimated budgets for the project, as well as sequences of tasks on different fronts such as the development of fully-coupled binational groundwater-surface-water models.

3.1.7. Communication and stakeholder engagement

Until a formal agreement between the two countries was signed, no binational work could proceed. The long development phase for this project (3 years prior to the signing of the Joint Report) runs counter to typical project timelines for hydrologic studies. This period, however, was needed for essential activities such as team and trust building (Bagshaw et al., 2007), as well as the time required drafting and negotiating the Joint Report and for the approval process in each country. Meetings and field trips were essential to the creation of the Joint Report and to building the binational Arizona-Sonora team. Much learning, negotiation, and within-country consultation had to occur in order to develop the team's ability to negotiate the complexity of institutional and cultural asymmetries. For hydrologic studies, there is no substitute for being physically present in the field area, but it became clear that field trips were opportunities not only for knowledge exchange, but also for building trust and a shared history.

Knowledge gained through the binational TAAP effort will be useful only if stakeholders are aware of the results of our research and given opportunities for interaction and communication with project scientists. The objectives stated in Public Law 109–448 require that US TAA funding be used to "produce scientific products for each priority transboundary aquifer that—(A) are capable of being broadly distributed; and (B) provide the scientific information needed by water managers and natural resource agencies on both sides of the United States-Mexico border to effectively accomplish the missions of the managers and agencies." Our definition of stakeholders includes the public, decision makers, and natural resource agencies who can use the research and information developed by the Arizona/Sonora section of the TAAP to improve understanding and inform decisions related to San Pedro and Santa Cruz aquifers. The WRRC and USGS have conducted forums to share information and to discuss future directions for studying the TSPA. Efforts were made to determine the most effective means of communication with stakeholders in the US and Mexico. Web products, factsheets, and briefings are an important mode of communication with stakeholders. The WRRC hosts a bilingual webpage (https://wrrc.arizona.edu/TAAP) that is regularly updated and includes background information on the program, links to publications, materials and activities, databases and workshops. A bulletin summarizing results of the *Binational Study of the Transboundary San Pedro Aquifer* was released in spring 2017 in both English and Spanish with the objective of showing the main results of the San Pedro study to interested stakeholders beginning June 20, 2017. Briefings with decision makers were also an important means of communicating results and listening for feedback on priorities.

3.1.8. Communication internal to the project

Protocols established by the IBWC were followed in order to achieve effective internal communication within and between the US and Mexican teams. Binational Technical Group meetings were scheduled by the IBWC. At these meetings new tasks were developed, and current challenges and progress were reviewed. Official minutes were produced for each session. Traveling to meetings continues to offer challenges. Depending on the institution, binational travel can require a complicated process to obtain permission for international travel and up to nine weeks advance notice. Conference calls are the default therefore for convenience and when time is insufficient to process travel arrangements. Informal peer-to-peer communication took place in the form of email and telephone exchanges, but only after permission was given by the IBWC.

3.1.9. Communication with the scientific community

Attendance and participation at conferences were important for communication and exchange among peers in the scientific community (for example: Callegary et al., 2009; McAndrew et al., 2009; Megdal et al., 2010; Scott et al., 2010; Minjárez et al., 2017; Vandervoet et al., 2013). In 2017, the binational team presented The Joint Cooperative Framework for the Transboundary Aquifer Assessment Program during a special session about the shared waters of North America at the World Water Congress in Cancún, México. Presentations included a poster on the TAAP and a discussion of the Joint Report and the *Binational Study of the Transboundary San Pedro Aquifer* (Callegary et al., 2017; Megdal, 2017). At the 2017 Universities Council on Water Resources Annual Conference, scientific and modeling efforts were presented, including discussions of the institutional and legal aspects of the TAAP. Journal articles, theses, and reports have also been critical to dissemination of scientific results (McAndrew, 2011; Megdal and Scott, 2011; Milman and Scott, 2010; Prichard and Scott, 2014; Scott et al., 2012; Stewart, 2014; Stewart et al., 2012). The *Binational Study of the Transboundary San Pedro Aquifer* was published in December 2016 and is the first binational aquifer study prepared and released simultaneously in English and Spanish by the IBWC (Callegary et al., 2016). The Santa Cruz study is currently under review by different governmental agencies in the US and Mexico and is expected to be completed in 2018.

3.2. Developing physical context

In this section, we briefly describe the assessment results of each of the main topics studied in developing the physical context. More specific results the physical-technical assessment either have been or will be published elsewhere (Callegary et al., 2016).

3.2.1. Delineation of the study area, literature review, and binational database development

One of our first tasks was to define the area of study. It was assumed initially that watershed boundaries, primarily following the crests of mountain ranges, would suffice. In Arizona, a decision was made to limit the size of the study areas of the two aquifers to downstream boundaries established by ADWR (ADWR, 1991). In Mexico, aquifers are defined legally, and generally approximate watershed boundaries, but tend to include portions of adjacent aquifers. This could have been a point of difficulty, since portions of the actual aquifers might be excluded from study. It was agreed however that the actual watershed boundaries could be used for the purposes of research/assessment in the binational study, for instance with groundwater modeling. In Sonora, the TSPA and TSCAS follow the official aquifer boundaries designated by the Mexican National Water Commission (CONAGUA) (CONAGUA, 2015a, b, c). For the TSCAS, the Arizona boundary combines three areas: the ADWR Santa Cruz AMA boundary (ADWR, 2017), the San Rafael Valley watershed (ADWR, 2014), and the Sonoita Creek Watershed which were added on the basis of watershed boundaries.

The next steps included reviewing existing literature and databases. Issues such as data integration and compatibility that were expected to be straightforward sometimes required time and face-to-face meetings to resolve. Questions arose regarding differences in measurement methods and dates, data review requirements, and Quality Assurance/Quality Control procedures. Decisions had to be made about which data fields to combine and which to leave out as well as negotiations regarding format, type (cations, trace metals, etc.), amount (e.g. all data or every other data point) and range of dates of data to be included. To fill data gaps in Sonora, a campaign of data collection was carried out by UNISON during that year (Minjárez Sosa et al., 2011a, b). A critical step was metadata development for each dataset. Required are the originator and publisher of the data, if modifications were made or if data are derived from calculations or modeling. For spatial data, required information included horizontal and vertical datums, and preferably instrument type or an estimate of precision. Finally questions regarding data storage location and level of accessibility (e.g. available to public?) needed to be answered.

3.2.2. Climate, land cover, vegetation, soils, and geology

Binational versions of some data types, such as land use-land cover and vegetation, were available in the published literature; however, challenges to data integration were the rule rather than the exception. It was a high priority to keep data and grid resolutions comparable on both sides of the border. For example, coverage provided by meteorological stations was insufficient to allow reasonable interpolation. Thus, it was decided that global meteorological datasets, though low in resolution, provided the best available data collected according to documented and reviewed methods. Soil data could not be integrated, because classification methods in each country differ significantly. For geology, rather than attempt to re-map each unit and bring descriptions into accord, it was decided to combine geologic units by age and rock type using geologic maps from each country.

3.2.3. Hydrology and hydrochemical data

Differences in amount, type, timing, and method of data collection presented a number of challenges to data integration in maps and databases. For example, methods for evaluation of water use differ in each country. In Mexico, reports on water availability including water budget are published for each legally-defined aquifer (CONAGUA, 2015a, 2015c). These are required to be updated every five years using standardized methods published in the Norma Oficial Mexicana NOM-011 – CONAGUA- 2000 (Diario Oficial de la Federación, 2002). The reports include information on geology, hydrology, and well censuses. They also calculate a groundwater budget for each aquifer and estimate the volume of water in deficit or the volume available annually for consumption. In the US, there are no uniform requirements for development of water budgets or the methods used to evaluate them. In the San Pedro and Santa Cruz aquifers, published water budgets exist, though different methods were used to compute them (Erwin, 2007; Gungle et al., 2016; Nelson, 2007). Thus, direct comparisons of water budgets were not possible. As in other areas of the project, compromise and accommodation were the norm. Selection of parameters depended on agency preferences and recommendations, as well as on the previous data available and the length of record. For instance, Mexican authorities expressed their interest in the distribution of major cations and anions (Na^+, Ca^{2+}, Mg^{2+}, K^+, Cl^+, SO_4^{2-}, HCO_3-) and US counterparts were interested in the distribution of isotopes in the study area. In addition, for both hydrologic and hydrogeochemical data, CONAGUA typically uses contour lines for presenting this type of information, whereas the USGS representatives prefer point information. A compromise was reached in which water-level maps used contours and water quality maps did not.

3.3. Lessons learned: challenges and solutions

Challenges arose from a variety of situations including (1) misunderstanding regarding the correct channels through which to carry out the binational work, (2) misunderstanding the correct protocols to use and (3) inadvertently differing interpretations of terms. The situation in (1) occurred early in the program when the US part of the team assumed that it could work directly with the states in Mexico and that no official binational agreement was needed. An example of (2) occurred when the US team did not send proposals for new binational tasks well ahead of binational technical advisory committee meetings, but instead introduced them during the meeting itself, resulting in rejection of the majority of the proposed tasks. An example of (3) occurred with the use of the acronym "TAAP". For a time after the signing of the Joint Report, the US team continued to use it to refer solely to projects receiving funding under the 2006 US TAA Act, while the Mexican portion of the team used it to refer to the overall binational program, resulting in confusion and ultimately the cessation of binational work in the Mesilla Aquifer for several years ending in 2016 when binational engagement was reinitiated. Each of these misunderstandings resulted in substantial delays of work or progress project-wide or with groups associated with particular aquifers.

The majority of the **solutions** to the challenges above were rooted in the domain of social rather than physical science, and often appeared with the benefit of hindsight. In an attempt to systematize them, we have laid them out in a diagram indicating the category or "element" being considered and the questions or factors that may be considered during project planning and implementation (Fig. 3). It is intended to be used flexibly, not prescriptively, being modified to fit the needs of each project or study.

3.3.1. Laying the groundwork

A long lead time between the passage of the TAA Act in 2006 and the signing by IBWC of the Joint Report in 2009 belies the intense activity of the intervening years. We label this phase "laying the groundwork" and in hindsight it was critical in that it made possible the ensuing binational studies. Critical activities during this period consisted in learning, engagement, team building, and development of binational understandings and protocols regarding communication and data exchange. Learning consisted of studying institutional and legal frameworks, and socio-political differences, as well as literature reviews, and building bibliographic and hydrologic databases. Engagement included convening stakeholders (the public, decision makers, and natural resource agencies) to explain project goals and context, and to solicit feedback on priorities, future directions, and tasks. Team building consisted of meetings and field trips with current and potential team members to build shared history and exchange understanding of and ideas about US and Mexican national and transboundary social, economic, legal and institutional frameworks as well as approaches to

Fig. 3. A distillation of lessons learned: selected social science elements used within the TAAP study.

scientific assessment of the aquifers. The eventual development of a common understanding of protocols and expectations with respect to communication and data exchange was critical for smooth functioning of the project. All of these steps helped to alleviate the perceived risk of engaging in this activity for both parties (Subramanian et al., 2012; Petersen-Perlman and Wolf, 2015).

3.3.2. Leadership and facilitation

Leadership and facilitation were key factors in the success of the TAAP. Leaders appeared at various junctures and ranged from decision- and policy-maker involvement in the creation of the TAA legislation to university- and agency-based managers and other personnel. Upper level managers at universities and agencies provided vision and guidance, and support in terms of keeping the program a priority at the institutional level. Leaders on the technical teams were responsible for maintaining high standards for the collection and analysis of scientific data, and organizing tasks and workflow. With respect to facilitation, various actors, both individuals and institutions, facilitated many processes and components of the program from stakeholder engagement and bridging cultures to scientific assessment. The organization that provided primary binational facilitation was the IBWC which has facilitation as one of its primary functions. In some respects, it combines some of the qualities of both bridging and boundary organizations as defined by Crona and Parker (2012). As such, it provides a space for trust building, learning, and conflict resolution by linking binational institutions ("bridging"); and it focuses on the science-policy interface in terms of water, and promotes accountability through the construction of agreements such as Minutes and the Joint Report ("boundary").

3.3.3. Available resources: technical and financial

The TAAP is a partnership of multiple institutions in two countries with differing technical and financial capacities. The diversity of institutions involved added flexibility and stability to the project. With respect to technical functions, a variety of modes (for example, stakeholder engagement and subcontracting) were used to extend the range of technical input and expertise. With respect to financial capacities, the diversity of institutions and timing and sources of funding supported stability and consistency of effort through time.

3.3.4. Adaptation-accommodation-perseverance: dealing with complexity and the unexpected

We have already noted the complexities and the learning process involved in blending physical and social science, with institutional asymmetries, differing funding cycles, shifting institutional priorities, and personnel changes. All of this occurs in the context of a shared binational history and different cultures and languages. Given that relationship building, process development and formalization, and scientific research are all occurring simultaneously within this temporally evolving environment, there should be no expectation that the perfect formula or institutional arrangement will be created (Varady et al., 2013). In such circumstances, adaptation, accommodation, and perseverance become not just significant factors, but factors that are critical to success.

3.3.5. Cultural and socio-political sensitivity

Cultural and linguistic considerations may seem irrelevant to most physical scientists, but disregarding them in a binational context can strain incipient relationships among participants. Having some members from each country with a working knowledge of the other country's culture and language made the work flow more easily. Despite the best efforts, however, breaches of institutional, hierarchical, and cultural norms continue to arise, and in fact, should be expected. A history of good will and trust can help to overcome such challenges. Important considerations when preparing for meetings include such basics as expectations for greetings (phrases and physical contact), and behavior and protocols (e.g. hierarchical formal discussions or unstructured discussions with at-will participation).

We assert that it is critical that cultural and socio-political issues be anticipated and respected from the beginning of a project (Blomquist and Ingram, 2003; Norman and Bakker, 2005). Far from reaching what is typically considered to be the main goal of aquifer assessments, a project that does not incorporate and act on this knowledge runs the risk of failure almost before it has begun. Factors that need to be considered initially, that may not occur to most physical scientists, are legal and institutional frameworks, especially those governing water management. A number of questions related to these factors arise that need to be answered. For example: who must be consulted? What are the protocols for consultation? Are there existing treaties, precedents, working groups? What work has already been done and who are the experts? These questions are logical when thinking about legal and institutional frameworks; however, it is also useful to think intuitively about what might have been missed. For instance, what questions are not being asked? Participants must be on the lookout for cultural biases and how they might be affecting interactions. During meetings, have all participants been asked individually to voice an opinion? Might there be cultural factors that affect reactions to such a question, and might there be a better time, place, and setting for eliciting this information?

3.3.6. Time

Estimates of time are typically incorporated into plans for scientific studies, but initial estimates in this case neglected to add time for negotiation, learning, and the unexpected. A general inability to predict time requirements for different tasks has been a recurring phenomenon in this study. Such is probably true of any bi- or multi-national project, and it is certainly true of the study of transboundary aquifers.

3.3.7. Research methods, data, and publication

Here the devil is in the details. Data collection (methods, frequency, metadata, storage, and accessibility) differed among agencies, institutions, and countries. Many tasks that are typically straightforward required significantly more time than expected due to problems of integration and compatibility. How to integrate had to be agreed upon largely after data collection occurred. Nationally adopted standards and methods for report formats and level of detail, peer review, data sharing, and translation all had to be had to be discussed. Reports format and level of detail eventually developed into a hybrid of the USGS and CONAGUA styles. Review of reports followed the usual protocols of each institution in each country. For data sharing, it was written into the agreement that the IBWC would be the official repository of records generated by all binational interactions, including joint projects.

4. Conclusions

The Transboundary Aquifer Assessment Program (TAAP), as applied to the San Pedro, Santa Cruz, and Nogales aquifers, has been a successful collaboration by government and university partners in Mexico and the US. TAAP was motivated by the TAA Act by the US Congress in 2006 with a ten year authorization, and developed within the context of worldwide advances toward transboundary aquifer assessment and governance promulgated by academics, UNESCO and other international bodies beginning in the 1990s.

One of the most significant achievements was the signing in 2009 by both countries of the Joint Report which created the US-Mexico Transboundary Aquifer Program. This authorized the formation of binational teams and the beginning of the truly binational phase of the technical studies. US TAAP funding was not appropriated during the period FY11 to FY15. Despite this, two projects that were initiated binationally were the development of reports for the transboundary San Pedro and the combined Santa Cruz and Nogales aquifers. The 2016 report on the TSPA compiles and analyzes scientific information from both countries (as will the TSCAS report), summarizing the current state of knowledge with the respect to hydrology and hydrologically related information.

Results of the TAAP build a foundation for understanding and can be used by agencies, land managers, universities, and decision-makers to make informed choices about current and future water resources. Moreover, bilingual binational reports focused on individual aquifers represent a store of hydrologic information from both countries that was previously unavailable in both languages in one publication. Maps included in the reports can be used by agencies, land managers, universities, and decision-makers to understand the way in which information on water, geology, climate, and vegetation is integrated across the border. The mapping effort is noteworthy in that data from each country were integrated across the border, thereby avoiding the customary "white map syndrome" on the other side of the border.

The process of carrying out the TAAP project has produced an experienced binational team, a tested process, and a precedent for a binational partnership of government institutions and universities, which can be used to facilitate and carry out new binational projects focused on transboundary aquifers. Data gaps were identified, including information and analysis necessary to update the numerical model of the groundwater flow system. The 2016 report, *the Binational Study of the Transboundary San Pedro Aquifer* (Callegary et al., 2016), is the first groundwater focused-report in which the data and results are officially accepted by the US and Mexican Governments through the IBWC. Official IBWC approval and participation was critical to project success; and working within the protocols outlined in the IBWC Joint Report led to an unprecedented level of data sharing and scientific cooperation between the two countries on the subject of groundwater.

We feel that the methods developed in this paper, if used appropriately and flexibly, will help to fill data gaps, add skill sets, and build relationships in those areas in which typical aquifer assessments are weakest and where transboundary aquifer assessments are most in need: socio-political and historical information, governance, legal and institutional frameworks, cultural sensitivity, communication and stakeholder engagement among others.

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Appendix A. Supplementary data

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