Journal of Hydrology 535 (2016) 101–119

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Identifying and characterizing transboundary aquifers along the Mexico–US border: An initial assessment

Rosario Sanchez [a,*], Victoria Lopez [b], Gabriel Eckstein [c]

[a] Water Management and Hydrological Sciences Program, Texas A&M University, MS 3408 TAMU, College Station, TX 77845, United States
[b] Water Management and Hydrological Sciences Program, Texas A&M University, United States
[c] Texas A&M University School of Law, International Water Law Project, United States

ARTICLE INFO

Article history:
Received 29 October 2015
Received in revised form 15 December 2015
Accepted 26 January 2016
Available online 3 February 2016
This manuscript was handled by Geoff Syme, Editor-in-Chief, with the assistance of Craig T. Simmons, Associate Editor

Keywords:
Transboundary
Aquifer
Mexico
United States
Management

SUMMARY

The transboundary nature of water dividing Mexico and the United States (U.S.) transforms the entire border region into an instrument of cooperation, a source of conflict, a national security issue, and an environmental concern. Reasonable data collection and research analysis have been conducted for surface waters by joint governmental institutions and non-governmental bodies. However, with the exception of the U.S. Transboundary Assessment Act Program (TAAP) (focusing on the Hueco Bolson, Mesilla Bolson, San Pedro and Santa Cruz aquifers), there is no comparable research, institutional development, or assessment of transboundary groundwater issues on the frontier. Moreover, data collection and methodologies vary between the two countries, there is no broadly accepted definition of the transboundary nature of an aquifer, and available legal and policy frameworks are constrained by non-hydrological considerations. Hence, there is a conceptual and institutional void regarding transboundary groundwater resources between Mexico and the U.S. The purpose of this paper is to bridge this void and characterize transboundary aquifers on the Mexico–US border. It reviews existing international frameworks for identifying hydrological and social criteria that characterize an aquifer as transboundary. It then assesses data from both countries to propose where and which aquifers could be considered transboundary. Finally, the paper proposes an agenda for assessing Mexico–US transboundary aquifers as a means for improving groundwater management in the border region.

1. Introduction

The transboundary nature of water dividing Mexico and the United States (U.S.) transforms the entire border region into an instrument of cooperation, a source of conflict, a national security issue, and an environmental concern. Reasonable data collection and research analysis have been conducted for surface waters by joint governmental institutions and non-governmental bodies. However, with the possible exception of the U.S. Transboundary Assessment Act Program (TAAP) (focusing on the U.S. sections of the Hueco Bolson, Mesilla Bolson, San Pedro and Santa Cruz aquifers), there is no comparable research, institutional development, or assessment of transboundary groundwater issues on the frontier. Overall, joint groundwater management practices are non-existent and unlikely in the near term.

The Mexico–U.S. case is not unique. Globally, over 600 transboundary aquifers have been mapped since 2003 by the International Groundwater Resources Assessment Centre (IGRAC), an initiative of UNESCO and the World Meteorological Organization. Yet, of these, only one is managed collaboratively (Genevese Aquifer shared by France and Switzerland), one has rudimentary extraction controls (Al-Sag/Al-Disi Aquifer shared by Jordan and Saudi Arabia), and two others in northern Africa (Nubian Sandstone Aquifer and Northwestern Sahara Aquifer) have data sharing arrangements (IGRAC, 2012, 2014).

According to the United Nations International Decade for Action ‘Water for Life’ 2005–2015 Program (UNDESA, 2014), research and data exchange has increased considerably for the 276 transboundary river basins found around the world. Moreover, after the entry into force of the 1997 U.N. Watercourse Convention (Watercourse Convention) in August 2014, a more rigorous effort for transboundary surface water management is expected to develop as water scarcity continues to challenge transboundary water systems internationally.

In contrast, the expectations for transboundary aquifers are more modest. Apart from the mapping program pursued by IGRAC, transboundary data exchange and cross-border research

* Corresponding author. Tel.: +1 979 845 2027.
E-mail address: rosario@geos.tamu.edu (R. Sanchez).

http://dx.doi.org/10.1016/j.jhydrol.2016.01.070
0022-1694/

development are not common. Additionally, while the Watercourse Convention does apply to some transboundary aquifers, its primary focus is on transboundary rivers and lakes (Eckstein, 2005). Moreover, the development of an international legal framework focusing on all shared groundwater resources is limited to a set of draft general principles proposed by the United Nations – the 2008 Draft Articles on the Law of Transboundary Aquifers.

While the existence of these instruments may appear promising, both the 1997 U.N. Watercourse Convention and the 2008 Draft Articles on the Law of Transbounday Aquifers are limited to 'general' principles that do not necessarily encompass the diversity or complexity of transboundary groundwater systems around the world. Numerous concerns related to the unique geological, climatic, and other natural conditions that characterize various transboundary aquifers, as well as the 'functioning' of different aquifers (e.g., disparate capacities to store and transport water, dilute contaminants, transmit geothermal heat, and serve as a habitat or water source for aquifer-dependent species) (Eckstein, 2011a), marginalize the countless hydrogeological conditions of groundwater resources around the world. There are also no international recognized guidelines for defining the boundaries of a transboundary aquifer system, and methodologies and principles for data-sharing tend to be decided by sovereign priorities, which might not necessarily be compatible with a holistic basin approach for groundwater management.

These conditions are also present in the Mexico–U.S. border. There is no consensus on the number of transboundary aquifers between Mexico and the U.S. At the international level, the International Shared Aquifer Resources Management Agency (ISARM) recognizes 11 transboundary aquifer systems (IGRAC, 2014); in Mexico, the National Water Commission (CONAGUA) reports 36 aquifers bordering the U.S, but officially only identifies the same as ISARM (CONAGUA, 2014). In contrast various research from the U.S. suggests that there may be as many as 38 (12 on Mexico's border with California, 9 with Arizona, 8 with New Mexico, and 9 with Texas) (ADWR, 2013; CDWR, 2014; George et al., 2011; Hawley et al., 2000). Although there is no official number recognized by the United States federal government (GNEB, 2010), the 15th report of the GNEB (Good Neighbor Environmental Board) mentions 20 transboundary aquifers but offers no additional information (GNEB, 2012). Other studies suggest a range of between 8 and 20 transboundary aquifers in the Mexico–U.S. border region (Eckstein, 2013; Mumme, 1988, 2000).

In addition, data collection and methodologies vary considerably between the two countries. Among the international community, as well as between Mexico and the United States, there is no broadly accepted definition of the transboundary nature of an aquifer or agreement on defining the boundaries of aquifers. Moreover, available legal and policy frameworks are constrained by non-hydrological considerations. The "blank map" syndrome, a condition in which researchers on either side of the border only describe the portion of the aquifer located within their side and leave the other side blank or delineate the border of the aquifer in relation to the international boundary (GNEB, 2010), still governs the interaction of transboundary hydrological systems in the border region, leading to incomplete and bias assessments in both countries. Hence, there is a conceptual and institutional void regarding transboundary groundwater resources between Mexico and the U.S. It is worth mentioning that challenges related to data collection and agreement on methodologies as well as lack of literature on characterization transboundary aquifers in the United States was first documented in the early 1970s by Bittinger (1972). The study characterized the severity of international and interstate aquifer problems for the United States' as 'major' or 'minor' based on survey responses from State water agencies and university personnel. Bittinger's work, however, did not seek to identify, delineate, or classify transboundary aquifers on the Mexico–U.S. border (Bittinger, 1972).

The purpose of this paper is to bridge the void in practice and in the literature and identify and characterize transboundary aquifers that cross the Mexico–U.S. border. It assesses data from both countries to propose, at various levels of confidence in relation to the available information, where and which aquifers could be considered transboundary. The analysis is intended to develop a foundation upon which further efforts could begin to characterize, categorize, and prioritize transboundary aquifers on the Mexico–U.S. border for purposes of enhancing groundwater management and decision making.

2. Methods

The approach used for this project included an array of targeted research to identify and analyze the data and information sought so as to provide as complete a foundation as possible for further study. Data collection included reviewing all available technical studies and raw data related to aquifers located on or near the Mexico–U.S. border that were generated by state and federal agencies, non-governmental organizations, and private researchers in both countries. It also included technical studies and publications discussing the governance framework administering transboundary aquifers on the border.

Building on the data collection effort, the study reviewed and analyzed the international, binational, and national efforts to characterize and classify aquifers as transboundary in the border region. It also assessed the hydrogeologic data related to frontier aquifers and identified gaps and inconsistencies in the information in an effort to begin characterizing the aquifers.

The analysis used ISARM's boundaries categorization as a reference for identifying aquifer boundaries in the border region. The *true/system aquifer boundary* refers to the limits of groundwater bodies with relatively high transmissivity and storage capacity, usually referred as the saturated zone. The *basin aquifer boundary* relates to the boundaries of the whole hydrological basin, which includes hydraulically connected groundwater systems. The *geological aquifer boundary* delimits the extension of the geological formation, which can potentially include aquifers but not necessarily across the entire unit. According to specific data, aquifer boundaries are sometimes defined by the funding available for the research project, therefore the aquifer extent could also be limited by budget considerations (Boghici, 2002; Timmons, 2014). Because Mexican and U.S. approaches for aquifer delimitation differ (Mexico uses basin aquifer boundary methodology exclusively, while the U.S. uses different approaches for different aquifers), Mexican data was used as the guiding reference for identifying and counting potential transboundary aquifers on the border. Where Mexican and U.S. data for a particular location conflicted, the Mexican data was used.

Based on the analysis, the study developed a new methodology to categorize transboundary aquifers based on available hydrological and institutional data. Three categories were created in relation to levels of confidence of the existence of a transboundary relationship: "reasonable," "some," and "limited." "*Reasonable*" level of confidence applies to aquifers for which the technical and related data evidencing a transboundary character was convincing. "*Some*" level of confidence applies to aquifers for which technical and related evidence was available but not definitive. "*Limited*" level of confidence refers to aquifers for which there is no technical data of a transboundary nature, but where some hydrological elements mentioned in technical studies, usually from only one side of the border, suggest the possibility of a transboundary aquifer. GIS is used to present the study's preliminary results for the entire border region.

3. Results

After collecting all available data to compile the puzzle of all the aquifers in the region and their potential transboundary nature, and using Mexico as the starting reference point, the data suggests the presence of as many as 36 transboundary aquifers along the Mexico–U.S. border, albeit with different levels of confidence of their transboundary nature.

Fig. 1 lists the preliminary results of the study. Of the 36 aquifers and aquifer basins identified, sixteen were categorized as transboundary with a "reasonable" level of confidence, while eight were categorized as transboundary with "some" level of confidence. There was limited hydrological, social, or other data available for the remaining twelve aquifers to classify them as potentially transboundary. Each aquifer will be addressed separately by state and region as follows.

3.1. Aquifers in the Baja California–California border region

Aquifer 1 is the Tijuana–San Diego Transboundary Aquifer (Fig. 1). On the U.S. side, California data indicates that this aquifer is divided into four groundwater alluvial basins: Tijuana, Otay,

STATES (MEXICO-US)	Confidence Level		
	REASONABLE	SOME	LIMITED
BAJA CALIFORNIA-CALIFORNIA	(1) Tijuana/San Diego- (Tijuana, Otay Sweetwater and Mission)		(2) Tecate/Potrero Valley and Campo Valley
			(3) La Rumorosa-Tecate/Jacumba Valley and Davies Valley
			(4) Laguna Salada/Coyote Wells Valley
BAJA CALIFORNIA-CALIFORNIA-SONORA-ARIZONA	(5) Valle de Mexicali/ Imperial Valley, Ogilby Valley, and Yuma Valley		
	(6)Valle San Luis Rio Colorado/Yuma		
SONORA-ARIZONA	(8) Sonoyta-Papagos/San Simon Wash	(7) Los Vidrios/Western Mexican Drainage	(10) Rio Altar/Tucson Active Management Area
	(12) Nogales/Santa Cruz (TAAP1)	(9) Arroyo Seco/Tucson Active Management Area	(11) Rio Alisos/Santa Cruz
	(13) Santa Cruz/Santa Cruz-San Rafael (TAAP1)		
	(14) San Pedro/San Pedro (TAAP2)		
	(15) Rio Agua Prieta/Douglas (INA)		
SONORA-ARIZONA-NEW MEXICO		(16) Arroyo San Bernardino/San Bernardino Valley-San Bernardino basin	
CHIHUAHUA-NEW MEXICO	(19) Los Moscos/ Hachita Moscos	(17) Janos/Animas and Playas aquifer basin	(18) Ascencion/ Hachita Moscos
	(20) Josefa Ortiz de Dominguez/Mimbres		
	(21) Las Palmas/Mimbres		
CHIHUAHUA-TEXAS-NEW MEXICO	(22) Conejos Medanos/Mesilla Bolson (TAAP3)		
	(23) Valle de Juarez/Hueco Bolson (TAAP4)		
CHIHUAHUA-TEXAS			(24) Valle del Peso/West Texas Bolsons
			(25) Bajo Rio Conchos/West Texas Bolsons
			(26) Alamo Chapo/Igneous
			(27) Manuel Benavides/Local aquifers
COAHUILA-TEXAS	(31) Presa La Amistad/Edwards	(29) Serrania del Burro/Edwards	(28) Santa Fe del Pino/Local aquifers
	(33) Allende-Piedras Negras/Local aquifers	(30) Cerro Colorado-La Partida/Edwards	(32) Palestina/Local aquifers
		(34) Hidalgo/Carrizo Wilcox	
NUEVO LEON-TEXAS		(35) Lampazos/Anahuac-Carrizo Wilcox	
TAMAULIPAS-TEXAS	(36) Bajo Rio Bravo/Carrizo Wilcox-Gulf Coast (Yegua Jackson no data)		
Total	**16**	**8**	**12**

Fig. 1. Transboundary aquifers between Mexico and the US: confidence level.

Sweetwater, and Mission Valleys (CDWR, 2014; Chavez-Guillen and Klein, 2007). On the Mexican side, the *Tijuana Aquifer* (as it is called in Mexico), as well as all aquifers in Mexico, is delimited by basin aquifer boundaries and, depending on the aquifer, by administrative boundaries (Chavez-Guillen and Klein, 2007; CONAGUA, 2008a). ISARM refers collectively to the four alluvial aquifer basins defined on the U.S. side, along with the Tijuana aquifer on the Mexican side, as the Tijuana–San Diego aquifer system (Chavez-Guillen and Klein, 2007). The complexity that arises from a simple physical concept differentiation between countries reveals the magnitude of the challenges awaiting the binational groundwater conversation.

The transboundary nature of the Tijuana–San Diego Transboundary Aquifer has been well documented by both countries with the Tijuana River as the main hydrological feature that connects the river to the aquifer. The river flows from the southern section of the city of Tijuana, Baja California, in a north-west direction recharging the aquifer in the valley on the Mexican side. The river then crosses the border with the U.S. and discharges into the Pacific Ocean just south of the city of San Diego, California. The geographic extension of the aquifer is small and its thickness is greater in the Mexican side (300 m) (Chavez-Guillen and Klein, 2007).

One of the main concerns for the Tijuana–San Diego aquifer is high salinity originating from agricultural runoff and untreated urban sewage seepage that infiltrate and recharge the aquifer. A related concern pertains to sea water intrusion along the coastal region on both sides of the border caused by over-pumping of the aquifer. Around 2.5 million people inhabit the cities of San Diego and Tijuana where irrigated agriculture and municipalities are the main users of groundwater. While both the Mexican and U.S. sides of the border are growing, the aquifer system experiences higher pumping rates on the Mexican side due largely to their faster population growth rates (San Diego 2.8% and Tijuana 4.9%) (Kiy and Kada, 2004). Some improvement in salinity levels were recorded after Mexico and California, with mediation by the International Boundary and Water Commission (IBWC), agreed to import more surface water from the Colorado River, construct a water treatment plant in California to improve the quality of Tijuana River effluent downstream, and ensure the conservation of the Tijuana River Mouth Marine Protected Area (Castaneda, 2013; Chavez-Guillen and Klein, 2007; Gersberg, 2005). Mexico has not reported any deficit in the aquifer (CONAGUA, 2008a). Nevertheless, CONAGUA data suggests that water levels in the aquifer south of Tijuana declined 5 m per year over the last twenty years (CONAGUA, 2008a). Based on the available data from both sides of the border, there is reasonable data to identify and categorize this aquifer as transboundary. Fig. 2 shows the aquifers identified between Baja California, Mexico and California, U.S. (CDWR, 2003, 2000; Hoel, 2013).

Aquifer 2 is the *Tecate Aquifer*, which has been identified on the Mexican side of the border, and the Potrero Valley and Campo Valley Aquifer basins in the U.S. side. According to available data, there is no evidence indicating a possible transboundary linkage between Tecate Aquifer and the aquifer basins in the U.S. side of the border (CDWR, 2014; CONAGUA, 2009a). As shown in Fig. 2, both Potrero Valley and Campo Valley are very small aquifer basins in comparison to the Tecate Aquifer, and only the Campo Valley Aquifer basin actually, but marginally, touches the border area.

There is limited data on both aquifer basins on the U.S. side (CDWR, 2014). Data from the Tecate Aquifer indicates low permeability in about 90% of the aquifer and concentration of alluvium material mostly on the Mexican side (Demere, 2005). Data from California does not report a water deficit in Potrero Valley and Campo Valley Aquifer basins. The same is true for the Tecate Aquifer. However, there are areas on the Mexican side with salinity issues due to the lack of sewage infrastructure. The main water users in the area include the Cuauhtémoc beer company and small communities (CONAGUA, 2009a). There is no detailed information on groundwater flow on the U.S. side, however, limited data suggests that it moves from east to west on the Mexican side and recharge comes mainly from precipitation (CDWR, 2014; CONAGUA, 2009a). Based on the available data from both sides of the border, the level of confidence of the transboundary nature of the Tecate Aquifer is limited.

Aquifer 3 is the *La Rumorosa-Tecate* (Mexican side) and Jacumba and Davis Valley Aquifer basins (U.S. side). Whereas the data from California is limited, considering the small size of the aquifer basins, La Rumorosa-Tecate Aquifer has been studied since 1982 as water demand has increased in the neighboring cities of Mexicali to the east and Tecate to the west (CONAGUA, 2008c). La Rumorosa-Tecate Aquifer in Mexico is located in the Arroyo Agua Grande sub-basin that extends into the U.S. as Arroyo Pinto Wash. The aquifer discharges into Arroyo Agua Grande, which flows east and drains the neighboring Laguna Salada endorheic sub-basin, though high evaporation rates in Laguna Salada region prevents any infiltration (CONAGUA, 2008c). There is no conclusive data to characterize this aquifer as transboundary or any recognition of its transboundary nature. On the Mexican side only 70 km^2 (of the total 739 km^2) in the southeastern part of the aquifer is considered to be an effective aquifer pumping area (CONAGUA, 2008c). The main water user in the region is agriculture and groundwater provides 95% of that supply. High levels of Total Dissolved Solids (TDS) have been reported on the Mexican side due to mining activity, and in the Jacumba Valley Aquifer in the U.S. as a result of over-pumping (CDWR, 2014; CONAGUA, 2008c). There is no groundwater deficit reported in the Mexican side (CONAGUA, 2008c).

The Jacumba Valley and Davis Valley Aquifer basins in the U.S. are considerably small in size and there is little data about either pertaining to their transboundary character (CDWR, 2014). Accordingly, the level of confidence of the transboundary nature of the La Rumorosa-Tecate and Jacumba Valle and Davis Valley Aquifer basins is limited.

Aquifer 4 is the *Laguna Salada Aquifer* on the Mexican side, and Coyote Wells Aquifer basin on the U.S. side. The Laguna Salada Aquifer underlies the municipalities of Mexicali, Ensenada, and Tecate in Mexico. In the U.S., available data is limited and only 374 inhabitants reside over the Coyote Wells Aquifer basin (CDWR, 2014). There is little data about either aquifer basin pertaining to a transboundary character. Fig. 2 shows that the northern extension of the Laguna Salada Aquifer that borders the Coyote Wells aquifer basin is small compared to the 5689 km^2 of total aquifer area in Mexico (CONAGUA, 2008b). The permeable area is located in the central part of the aquifer where the Laguna Salada lagoon used to exist (CONAGUA, 2008b). The area is surrounded by impermeable material that acts as boundaries for underground flow and recharge comes directly from precipitation (CONAGUA, 2008b). According to CONAGUA, the Laguna Salada Aquifer is an underexploited aquifer. The water table has remained constant over the last decade and in some areas, the recharge rate is higher than the pumping rate (CONAGUA, 2008b). On the U.S. side, available data indicates that the Coyote Wells Valley aquifer basin has experienced overdrafting, local fluoride issues, and high TDS in some of the shallower wells in the basin (CDWR, 2014). Based on the available data from both sides of the border, the level of confidence of the transboundary nature of the Laguna Salada-Coyote Wells Aquifer is limited.

Aquifer 5 is the *Valle de Mexicali Aquifer* in the Mexican side and Imperial Valley, Ogilby Valley, and Yuma Valley Aquifer basins in the U.S. side. The Valle de Mexicali Aquifer underlies and supports the most important agricultural region in Mexico, which extends to

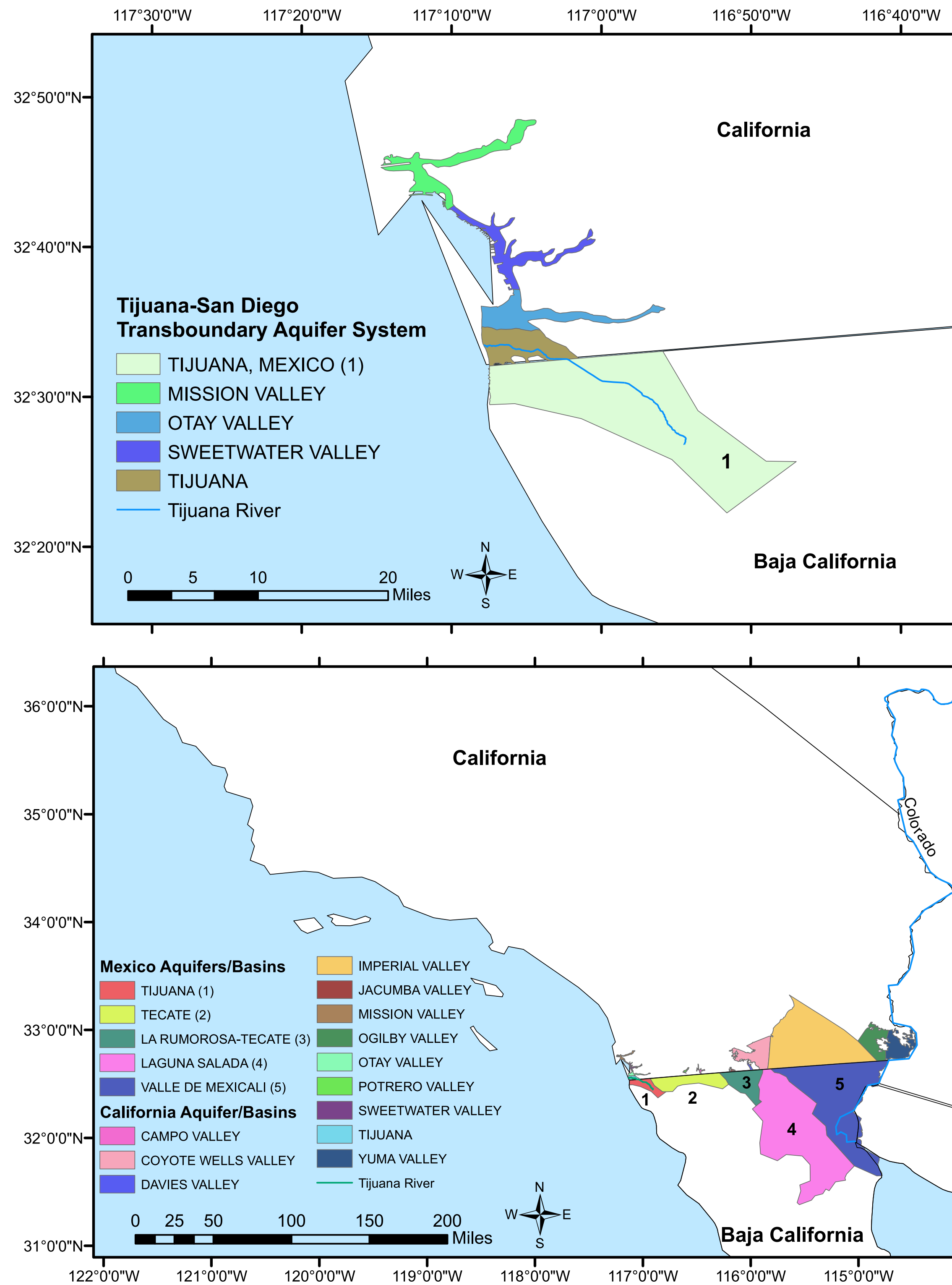


Fig. 2. Aquifers in the Baja California–California Border region.

the region overlying the Yuma Aquifer (Aquifer 6) on the U.S. side. Available data supports the groundwater linkages within this aquifers as groundwater flows from north to south parallel to the flow direction of the Colorado River (Chavez-Guillen and Klein, 2007; CONAGUA, 2009d; Mumme, 2000). Recharge comes directly by infiltration of the Colorado River, agricultural runoff, and horizontal flow (CONAGUA, 2009d). Based on the available data from both sides of the border, there is reasonable data to identify and categorize this aquifer as transboundary.

It is noteworthy that the importance of the surface–groundwater linkages in this region has led to intense conflicts between Mexico and the U.S. over the lining of the All-American Canal, which diverts water from the Colorado River in Arizona to Imperial Valley in California through an eighty-mile long canal running along the Mexico–U.S. border. According to Mexico, the 2009 lining of twenty-three miles of the canal with concrete has deprived the Valle de Mexicali Aquifer of significant groundwater recharge from seepage that had occurred regularly since the canal was constructed in the 1930s (Hathaway, 2011). The reduction in seepage has also affected the Andrade Mesa Wetlands located two miles south of the border in the delta of the Colorado River. The Wetlands were accidentally created in the 1940s and maintained by the seepage of the All-American Canal and eventually became a habitat of more than 100 species of birds, including the Yuma Clapper Rail, which has been listed under the US Endangered Species Act (Zamora-Arroyo et al., 2006; Hinojosa-Huerta et al., 2002). Recent studies indicate that after the canal was lined, the water within the wetlands, as well as groundwater levels on the Mexico side, declined significantly (Coes et al., 2015; Cortez-Lara et al., 2009; Gomez-Sapiens et al., 2013). In 2009, CONAGUA reported a deficit of 487 h m^3 and an annual decrease in water level of 0.25 m per year in the Valle de Mexicali Aquifer due to over pumping for agricultural production (CONAGUA, 2009d).

3.2. Aquifers in the Sonora–Arizona border region

Aquifer 6 is the *Valle de San Luis Rio Colorado Aquifer* in Mexico and the Yuma Aquifer in the U.S. This aquifer has been studied since the early 1960s due to its high hydraulic connectivity with the Colorado River, which constitutes the main source of water downstream in Baja California, Mexico, and Imperial Valley in California. The Colorado River is also the main recharge source for the Valle de San Luis Rio Colorado Aquifer in Mexico (ADWR, 2009a; CONAGUA, 2008d). The sensitivity of this linkage is particularly significant such that in 1973, both countries established the only existing groundwater agreement between Mexico and the U.S. in the entire border area as part of Minute 242 of the IBWC (IBWC, 1973). This transboundary aquifer also supports important transboundary ecological reserves, including El Pinacate volcanic peaks and Gran Desierto de Altar, and is critical for the ecosystems of Alto Golfo de California and the Colorado River Delta (CONAGUA, 2008d). There is no water deficit reported for this aquifer and groundwater quality is permanently monitored by the IBWC (CONAGUA, 2008d). Based on the available data from both sides of the border, there is reasonable data to identify and categorize this aquifer as transboundary.

Aquifers 5 and 6, are part of what is referred by ISARM as the Cuenca Baja del Rio Colorado Transboundary Aquifer System (Chavez-Guillen and Klein, 2007; UNESCO, 2010). The system encompasses the three aquifers basins in California (Imperial Valley, Ogilby Valley, and Yuma Valley) and the Yuma Aquifer in Arizona. It is not, however, defined, managed, or approached as a whole unit by any of the involved political jurisdictions (CDWR, 2014; CONAGUA, 2008d, 2009d).

Aquifer 7 is the *Los Vidrios Aquifer* in Mexico bordering the Mexican Drainage Aquifer basin in the U.S. There is no conclusive data that indicates the transboundary nature of this aquifer. This is an extremely arid region with a precipitation of around 68 mm where landscape is dominated by sand dunes and where the Altar Desert covers almost 80% of the aquifer area (CONAGUA, 2010c). This is an area of low population density with negligible pumping levels in the Mexican side (927 m^3 per year) and no significant increase of water demand on either sides of the border (ADWR, 2009h; CONAGUA, 2010c). However, some data suggests possible transboundary linkages in this aquifer. Arizona data has identified groundwater flow across the border from the smallest eastern part of the aquifer, which corresponds to the area of what ISARM identifies as the Sonoyta-Papagos Transboundary Aquifer system (Aquifer 8) (ADWR, 2009a; Chavez-Guillen and Klein, 2007). CONAGUA has suggested groundwater recharge also coming from the northern-west part of the Mexican Drainage Aquifer into Mexico, but data is not conclusive. Low elevations, high permeability and quality of water in the area have been used to report transboundary linkages in this aquifer (CONAGUA, 2010c). Likewise, some research suggests groundwater and surface linkages in the Quitobaquito Oasis area also known as Quitobaquito Springs located on the U.S. side just 590 feet north of the border. Quitobaquito Springs and pond is the largest water body in Organ Pipe Cactus National Monument Park. It is maintained by desert springs and is home of the Quitobaquito Desert Pupfish and the Sonoran Mud Turtle, both of which are listed under the US Endangered Species Act. The Gran Desierto de Altar Biosphere Reserve on the Mexican side of the border is considered Quitobaquito's sister park (Pearson and Conner, 2000). Data suggests that over pumping in the Sonoyta Valley on the Mexico side could threaten the survival of the Quitobaquito pupfish and its habitat, although there is no conclusive data on the relationship between the desert springs and the aquifer (Anderson, 1985; Pearson and Conner, 2000).

Aquifer 8 is the *Sonoyta-Puerto Penasco Aquifer* in the Mexican side, and the Simon Wash Aquifer basin in the U.S. This aquifer is referred as the Sonoyta-Papagos Transboundary Aquifer System by ISARM (Chavez-Guillen and Klein, 2007). See Fig. 3. The main hydrological feature of the transboundary linkage is the north–south flow of the Simon Wash river from Arizona into Sonoyta, Mexico, and groundwater following the same route (ADWR, 2009b; CONAGUA, 2009l). The Sonoyta-Puerto Penasco/Simon Wash Aquifer area is sparsely populated on both sides of the border. However, there are important water quality issues related to over-pumping rates particularly in Arizona. Close to 80% of the wells report arsenic levels, as well as TDS, chromium, fluoride, mercury, lead and nitrate, that equal or exceed allowable national standards (ADWR, 2009b). In the Mexican side, only 30% of the water is acceptable for potable use, 25% is suitable for agricultural purposes, and there is a reported deficit of approximately 80 h m^3 per year, though no cones of depression have been identified (CONAGUA, 2009l). Based on the available data from both sides of the border, there is reasonable data to identify and categorize this aquifer as transboundary. Fig. 3 shows the aquifers identified between Sonora and Arizona (ASLD, 1993; Fisher, 2015; Hoel, 2013; Megdal and Scott, 2011b; NMWRRI, 2002; NWS, 1999).

Aquifers 9 (*Arroyo Seco*) **and Aquifer 10** (*Rio Altar*) are addressed together as they both border the Tucson Aquifer basin in the U.S. See Fig. 3. There is no conclusive data that identifies these aquifers as transboundary. The Tucson aquifer is managed under Arizona's Active Management Area regulation, which imposes pumping restrictions due to the region's growing population (almost 800,000 in the central region) and dependency on groundwater for industrial and municipal use (ADWR, 2009f). Water quality issues are of highest concern due to intensive mining activity. The southern part of the aquifer bordering with Mexico does not show important population development and groundwater use and, therefore, monitoring of groundwater has been limited as compared to the central and northern portions of the aquifer (ADWR, 2009f).

In the Mexican side, the cities overlying the Arroyo Seco and Rio Altar aquifers, Altar and Saric, do not represent significant water-demanding urban centers (less than 10,000 inhabitants) and pumping is concentrated in the southern part of both aquifers (CONAGUA, 2009b). There is, however, literature suggesting some transboundary linkages. According to CONAGUA, Arroyo Seco River is an important source of recharge for the Arroyo Seco Aquifer. It flows from the north as Arroyo El Sasabe and El Fresnal in the U. S. in a southern direction into the alluvial recharge area in the Mexican side (CONAGUA, 2009b). Likewise, there is literature that references the underlying groundwater of the Pima County area as transboundary, but no further details are provided (Burman and Cornish, 1975; Paule, 1996). Therefore, data on Arroyo Seco Aquifer (Aquifer 9) suggests some transboundary linkages. Aquifer 10 (Rio Altar), on the other hand, apart from the main hydrological reference of having Rio Altar River headwaters in the mountains near

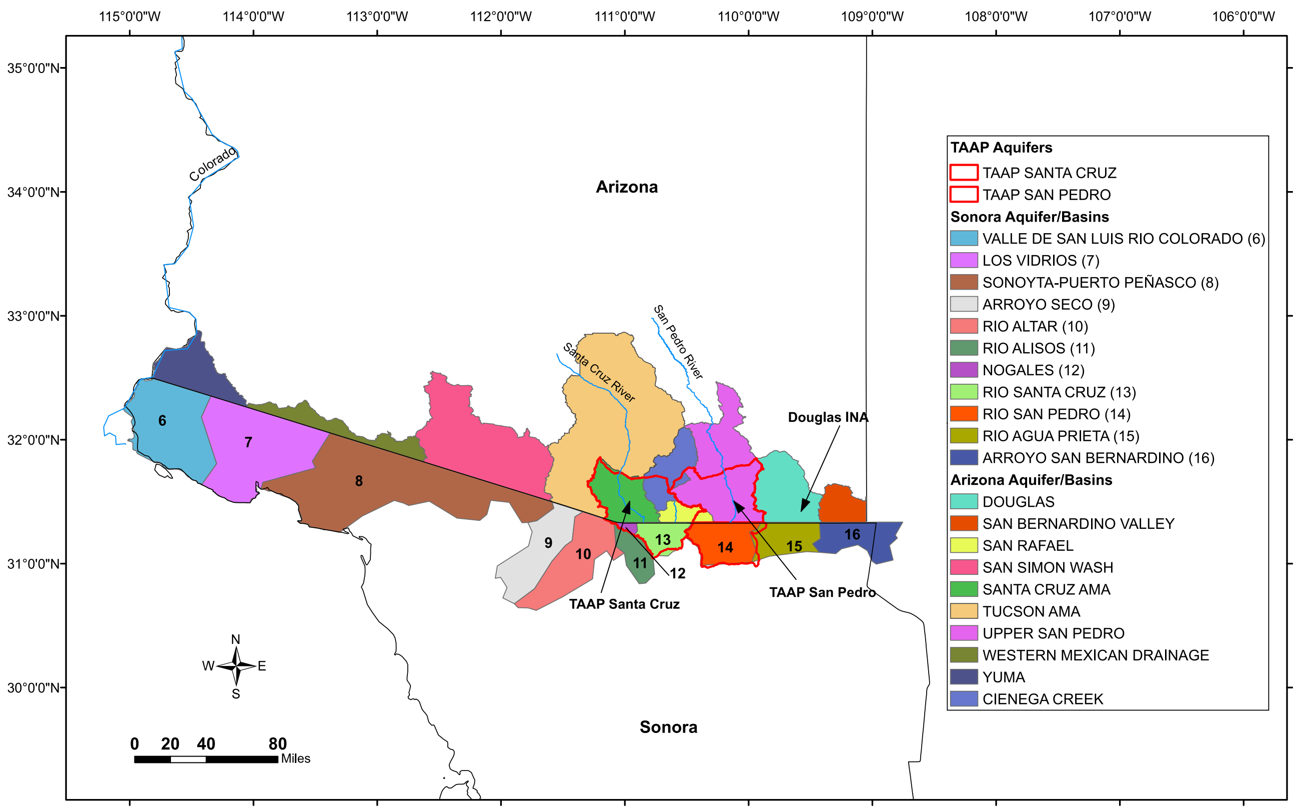


Fig. 3. Arizona–Sonora aquifer/basins.

the border with Pima County, and the north–south groundwater flow pattern, there is no additional information on its possible transboundary linkages with the Tucson Aquifer (CONAGUA, 2009e).

Aquifer 11 is the *Rio Alisos Aquifer* in Sonora, which borders the Santa Cruz Aquifer basin in Arizona. However, the aquifer section that actually borders the U.S. side is no longer than 3 km, and the rest of the northern border of the aquifer is just south of the limits of the *Nogales Aquifer* (Aquifer 12) which has been identified as transboundary and will be addressed below (Callegary et al., 2013). See Fig. 3. Rio Alisos Aquifer is comprised of sediment deposits in the bordering area of mainly low permeability granite material (CONAGUA, 2010d). The headwaters of the Rio Alisos, which is the main recharge source of the aquifer, is located in the Pajarito Mountains near the border and flows south across the alluvial aquifer. There is no available data to characterize this aquifer as transboundary or even link it to its eastern neighbor, the *Rio Santa Cruz Aquifer* (Aquifer 13) also identified as transboundary (Callegary et al., 2013; WRRC, 2011). There is no water deficit reported in the Mexican side (CONAGUA, 2010d).

One of the four transboundary aquifers assessed under the U.S. Transboundary Aquifer Assessment Program (TAAP) is the Santa Cruz Transboundary Aquifer. On the Mexican side, two aquifers are part of this program: *Nogales* (**Aquifer 12**) and *Rio Santa Cruz* (**Aquifer 13**), and on the U.S. side, the Santa Cruz Aquifer basin which also includes the San Rafael Aquifer basin as part of the same system (Callegary et al., 2013; Megdal and Scott, 2011a). See Fig. 3. Even though Aquifers 12 and 13 are identified separately in our categorization, based on our data from Mexico, they both border the Santa Cruz Aquifer in the U.S., which has proven to be strongly linked by the Santa Cruz Transboundary River and Arroyo Nogales. Accordingly, they will be addressed as part of the same transboundary hydrological system.

The cities of Nogales, Sonora, and Nogales, Arizona, both located in this aquifer region, are two of the fastest growing sister cities in the border area. Issues such as over pumping and declining water quality levels in a very strong surface–groundwater linkage have been historically challenging on both sides of the border (Megdal and Scott, 2011a; Wilder et al., 2011) and deserve extensive research and data collection (UNESCO, 2010). Arroyo Nogales originates 8 km south of Nogales, Mexico, and flows northward across the border toward Nogales, Arizona, where it becomes a tributary of the Santa Cruz River. The headwaters of the Santa Cruz River is located in the San Rafael Valley in Arizona and flows southward 6 km to Nogales, Sonora, before flowing north-west back to Nogales, Arizona. The drainage area of the Santa Cruz River is 1380 km^2, from which 73 km^2 corresponds to Arroyo Nogales. Around 63% of the aquifer is located in the Mexican side and the rest in the U.S. (CONAGUA, 2009c, 2009j). Groundwater flows parallel to the Santa Cruz River and the aquifer is characterized with strong transmissivity and permeability ranges on both sides of the border (ADWR, 2009e; CONAGUA, 2009j). It is estimated that annually around 3.4 h m^3 of groundwater from the Nogales Aquifer and around 2 h m^3 from the Santa Cruz Aquifer in Mexico flows northward into the U.S. side of the aquifer (CONAGUA, 2009c).

Groundwater is used in this region mainly for municipal and industrial purposes, followed by agricultural uses (mostly in Arizona). Water quality standards have reached risky levels of TDS and nitrates according to Mexican standards, and have exceeding acceptable limits according to U.S. standards (ADWR, 2009e; CONAGUA, 2009j). Interstate and binational cooperation through the IBWC, related to water treatment of the effluent flowing from the south in Nogales, Sonora, northward toward Nogales, Arizona, is well documented (Blanco et al., 2001; Eckstein, 2011a; Hathaway, 2011). The boundaries of the aquifers, however, are not clearly agreed upon. ISARM and CONAGUA identify the Nogales and Santa Cruz aquifers as two independent aquifers (CONAGUA, 2009c, 2009j), as compared to the holistic approach taken by the TAAP, which delineates the two as comprising a single system regardless of the political jurisdiction. ISARM, in fact, only offers an approximation on the basin boundaries of the Nogales Aquifer in the U.S. side (Puri and Aureli, 2009).

The second TAAP aquifer is the *San Pedro*/San Pedro Transboundary Aquifer (**Aquifer 14**). See Fig. 3. As Aquifers 12 and 13, the boundaries of this aquifer in the U.S. side differ between the interpretation provided under the TAAP and that provided by the state of Arizona. For TAAP, only the Lower San Pedro aquifer basin is considered within the aquifer system, whereas at the state level, both the Lower and Upper San Pedro aquifer basin are regarded as part of the same basin (ADWR, 2009g; Callegary et al., 2013). ISARM also seems to recognize both the Lower and the Upper San Pedro basin in the U.S. side as one aquifer, but the limits are only approximate (Puri and Aureli, 2009).

Research has demonstrated strong hydrological surface–groundwater linkages in the system. The San Pedro Aquifer in Mexico underlies the cities of Cananea and Naco with approximately 40,000 inhabitants where groundwater is mainly used for mining activities. In Arizona, the San Pedro Aquifer is used mainly for agriculture (Megdal and Scott, 2011a). The San Pedro River's headwater is located near Cananea and it flows northward into Arizona until it joins the Gila River. Data has demonstrated that over-pumping, especially in the southern part of the basin (Mexico), has reduced the amount of water discharged into the San Pedro and Babocamari rivers in Arizona by about 30% (CONAGUA, 2010e). Additionally, between 1995 and 2000, the underground flow from Mexico to Arizona was reduced from 8 h m^3 to 1.3 h m^3 per year (CONAGUA, 2010e). This situation has significantly reduced the perennial flow into southern Arizona and was responsible for prompting federal U.S. action in 2004 to address conflicting water needs between endangered species and the Fort Huachuca military base (Megdal and Scott, 2011a; Wilder et al., 2011). Even though there has been no deficit reported on the Mexican side, CONAGUA has recognized that parts of the aquifer basin have been overexploited (CONAGUA, 2010e).

Aquifer 15 is the *Agua Prieta*/Douglas Transboundary Aquifer. Information on this aquifer offers reasonable confidence about the hydrological transboundary linkages, however, it has not been recognized as transboundary by CONAGUA, TAAP, ISARM or the state of Arizona (CONAGUA, 2009k, 2014; Hathaway, 2011; Mumme, 2000). The Arroyo Pinto River in the Mexican side flows northward to join the Whitewater River, which flows south again crossing the sister cities of Nogales (known in Mexico as Agua Prieta River). This river system drains the permeable alluvium area on both sides of the border. The aquifer discharges about 2.3 h m^3 per year into Arroyo Pinto and drains the central part of the aquifer in Arizona where recharge occurs mainly from irrigation seepage and river infiltration as the river flows south crossing the Mexican city of Agua Prieta (ADWR, 2009c; Burman and Cornish, 1975; CONAGUA, 2009k).

All water used in this basin in the U.S. side comes from groundwater and more than 75% is used for agriculture, mostly around the cities of Douglas, Pirtleville and Elfrida in Arizona. In contrast, in the Mexican side, 81% of groundwater extractions are used for meeting the municipal needs of the cities of Agua Prieta and Naco, while 16% is used for agriculture (ADWR, 2009c; CONAGUA, 2009k). Groundwater quality has been decreasing over time as irrigation has expanded in Arizona. Studies show that the aquifer now has levels of fluoride, arsenic, and nitrates equal to or exceeding U.S. drinking water standards. As a result, pumping restrictions have been implemented and a wastewater treatment facility installed (with support of the IBWC) to improve the quality of water discharged into Agua Prieta River in Mexico for irrigation purposes (ADWR, 2009c). There is no water deficit reported in the Mexican side (CONAGUA, 2009k).

3.3. Aquifers in the Sonora–Arizona–New Mexico region

Aquifer 16 is the *Arroyo San Bernardino*/San Bernardino Valley Basin Aquifer, which is shared by Sonora (1042 km^2), Arizona (1000 km^2), and the small extreme south-west corner of New Mexico (90 km^2). There is limited data available about the transboundary nature of this aquifer in Mexico and Arizona. Nonetheless, there is hydrological evidence of important cross-border groundwater linkages. Technical studies in New Mexico do recognize this aquifer as transboundary and provide information on groundwater linkages with both Sonora and Arizona (Hawley et al., 2000). Accordingly, the aquifer is designated as providing some degree of confidence of its transboundary character.

The aquifer is a recent alluvial formation with groundwater flowing from the northern part of the basin in Arizona southward into Mexico following the course of the Black Draw perennial stream (ADWR, 2009d; CONAGUA, 2008e). Its main recharge comes from scattered natural springs, precipitation from high surrounding mountains and stream infiltration along the alluvial area. There are no important communities in the area and water demand does not exceed the recharge in either side of the border suggesting that this aquifer is in a pre-development state. However, increasing groundwater pumping rates are reported in Arizona (ADWR, 2009d). According to technical studies in New Mexico, historic data indicates an absence of substantial. economically recoverable, groundwater supplies (Hawley et al., 2000). This aquifer is the sole source of water in the area and there is limited data related to water quality, though it is considered good water quality in the Mexican side (CONAGUA, 2008e). There is some concern in Mexico about the high extraction rates close to the border in Arizona that could possibly change natural groundwater flow (CONAGUA, 2008e). This aquifer does not show any challenges as far as water supply and water quality to a negligible population in the region (CONAGUA, 2008e).

3.4. Aquifers in the Chihuahua–New Mexico border region

Aquifer 17 is the *Janos Aquifer* in Chihuahua, which borders the Animas and Playas-San Basilio Aquifer basins in New Mexico. This aquifer has transboundary features, mostly in the Playas-San Basilio Aquifer basin, that are well documented by technical studies in New Mexico (Burman and Cornish, 1975; DBSandA, 2005; Hawley et al., 2000). However, data for this aquifer on the Mexican side is limited (CONAGUA, 2002b). According to the New Mexico studies, the portion of the Animas Aquifer that extends into Mexico is very small as compared to the total aquifer basin (90 km^2 of a total of 6025 km^2) (Hawley et al., 2000). See Fig. 4 (Fisher, 2015; Hoel, 2013; NMWRRI, 2002; NWS, 1999; NWS, 2014). While groundwater flows mostly from center to north-western corner of the aquifer basin in the U.S, the studies also indicate that some groundwater flows southward 40 km into Mexico (DBSandA, 2005). The aquifer basin boundaries in Chihuahua do not coincide with those in New Mexico. The Janos Aquifer seems to cover a much broader geographic area in the Mexican side and does not fit the puzzle pieces from the Animas and Playas-San Basilio aquifer boundaries in New Mexico (CONAGUA, 2002b; Hawley et al., 2000). Accordingly, the aquifer is designated as providing only some degree of confidence of its transboundary character.

Groundwater recharge for Aquifer 17 occurs from precipitation and percolation of local streams and some discharge is estimated to occur in the northeastern part of the basin. The Animas and

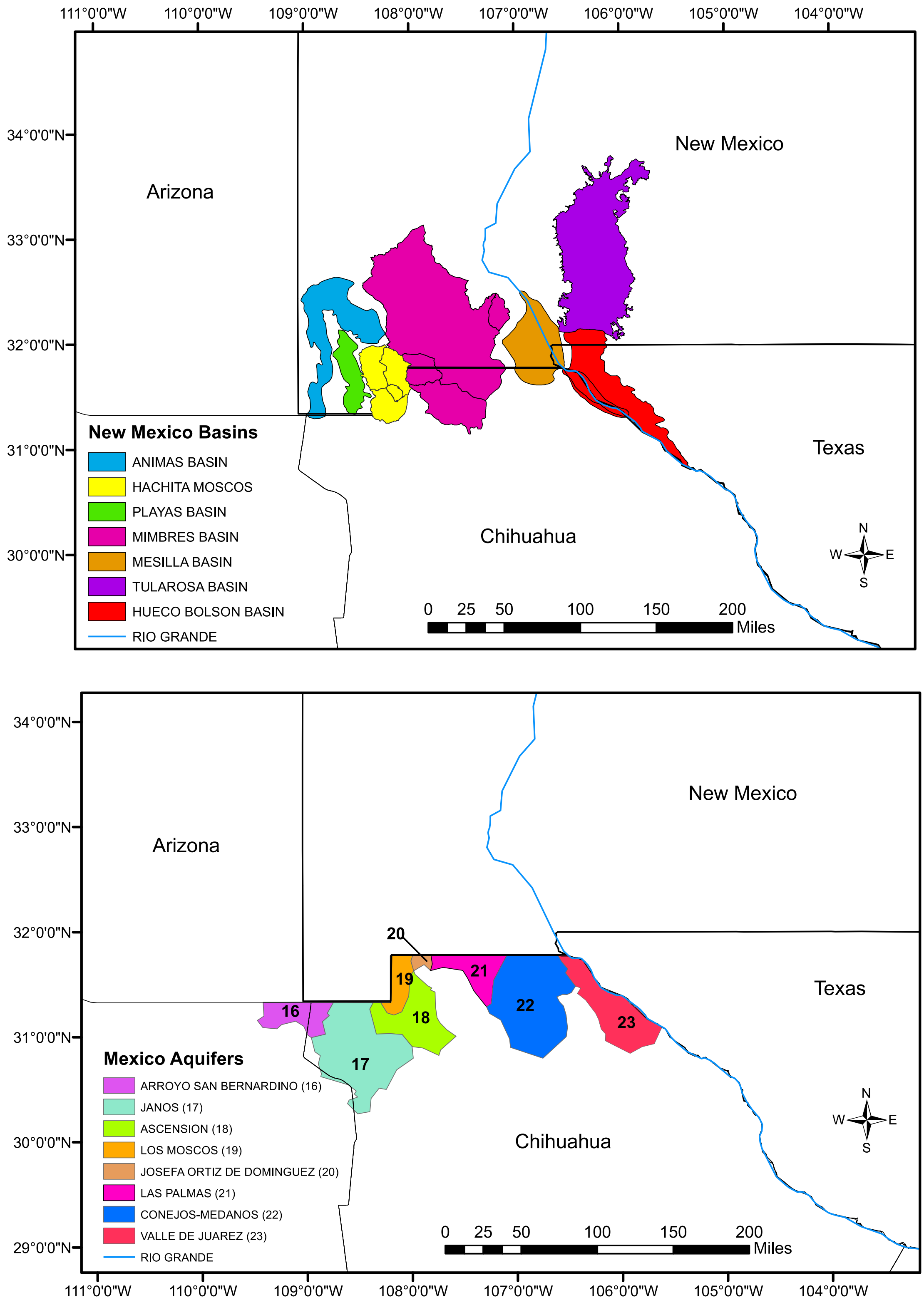


Fig. 4. Chihuahua–New Mexico aquifer/basins.

Playas-San Basilio aquifer basins are considered closed alluvial aquifers with no groundwater flow within their basins (DBSandA, 2005; Hawley et al., 2000; Vincent and Krider, 1998). This hydrological feature also suggests a lack of connection with the Janos aquifer in the Mexican side. Except for the basins' geographical extensions into Mexico, the rest of the Janos Aquifer in Mexico might be part of a separate aquifer system, possibly Ascension Aquifer (Aquifer 18) to the east. Further research is needed to confirm this possibility.

As for water use, most groundwater in New Mexico is used for rangeland followed by municipal use. Though this is a low density population area, overdraft has been recorded in the northern part of the Animas basin where the city of Lordsburg is located. In the U. S. side some groundwater is used in agriculture and the rest in mining activities surrounding the two urban centers: Playas and the border town of Antelope Wells–El Berrendo (DBSandA, 2005). In the Mexican side (Janos aquifer), more intensive groundwater use for agriculture has been recorded around the cities of Janos, Casas Grandes, part of Agua Prieta, and Bavispe. Recharge of the aquifer comes mostly from precipitation and agriculture runoff. The groundwater discharges into Casas Grandes and San Pedro intermittent rivers, which drain the area and supply water to the local irrigation district before discharging into the Laguna de Guzman, an endorheic or terminal lagoon. Some groundwater also discharges east into the Asuncion Aquifer valley basin (CONAGUA, 2002b). Water extraction is concentrated in the north-eastern part of the aquifer near the Playa-San Basilio Aquifer boundary area and is reported to be in overdraft condition with declining water tables averaging one meter per year (CONAGUA, 2002b).

Aquifers 18 and 19, the *Ascension and Moscos Aquifer* basins, respectively, in Chihuahua, border the Hachita-Moscos aquifer basin in New Mexico. Based on available data, only Aquifer 19 (Moscos) has been identified as transboundary with half of the aquifer basin in each country (CONAGUA, 2009h; DBSandA, 2005). Aquifer 18 cannot yet be characterized as transboundary. The aquifer delineation coincide on both sides of the border. Because the *Moscos Aquifer* (Aquifer 19) in the Mexican side is located completely within the *Ascension Aquifer* basin (Aquifer 18), the two aquifers will be addressed together for a better comprehension of the system. See Fig. 4.

The *Moscos* Aquifer in the Mexican side is considered to be a closed aquifer system that is recharged through groundwater flow coming from Hachita-Moscos Aquifer in New Mexico and from the Ascencion Aquifer (Aquifer 18) in Chihuahua. The Moscos Aquifer discharges into the Moscos Laguna in Mexico, another terminal lagoon that rapidly evaporates due to the extreme arid climate (CONAGUA, 2009h; Hawley et al., 2000). There are no perennial streams in the area, and no major groundwater pumping or deficit has been observed in either side of the border. The basin has been used primary for rangeland and no irrigated agriculture is present in the U.S. side. In contrast, there are around 80 wells in the Mexican side, mostly used for irrigated agriculture (CONAGUA, 2009h; DBSandA, 2005). Even though there is reasonable hydrological data to confirm the transboundary nature of Moscos Aquifer with the Hachita-Moscos Aquifer, the aquifer is not officially recognized as transbounary, neither on the Mexican side nor at the international level by IGRAC or ISARM.

The *Ascencion Aquifer* (Aquifer 18), on the other hand, is intensely used for agriculture production (97% of all ground water withdrawals), which is the main economic activity for at least 15 communities in the area, including the cities of Ascencion and Janos in the Mexican side. Groundwater levels are already showing an overdraft of around 1.5 m and a deficit of approximately 269 h m^3 per year (CONAGUA, 2002a). The most important surface water body in the region is the Casas Grande perennial river, which disappears at some points during the irrigation season and constitutes the most important recharge source for the Ascencion Aquifer. The aquifer eventually discharges into the Laguna de Guzman on the east side of the aquifer. Although there is no data on the transboundary nature of this aquifer, and while the physical area that borders New Mexico is limited in size (see Fig. 4), groundwater flows from this aquifer serve to recharge Aquifer 19 (Moscos) and some discharge also occurs into Moscos Laguna. Both Aquifers 18 and 19 seem to be hydrologically connected, but the endorheic character of Aquifer 19 do not seem to fully apply to Aquifer 18 in the same Hachita-Moscos transboundary basin system (CONAGUA, 2002a). Limited data, however, suggests the possibility that over-extraction of water in Aquifer 18 could develop cones of depression that could eventually impact groundwater recharge to Aquifer 19.

Aquifers 20 (*Josefa Ortiz de Dominguez*), and **Aquifer 21** (*Las Palmas*) in Mexico, and the Mimbres Aquifer basin in New Mexico, are referred in the literature as the Mimbres Transboundary Aquifer (Hawley et al., 2000). There is reasonable data to confirm the transboundary nature of this aquifer system and it has been recently recognized by ISARM (IGRAC, 2015). This is a very complex system with confined and unconfined areas, which vary in extent, aquifer delineation, surface–groundwater connections, and groundwater flow. Therefore, Aquifers 20 and 21 will be addressed together.

About 11,400 km^2 of the basin is located in New Mexico, while only 1900 km^2 is located in Chihuahua, though stream conveyance is concentrated in the Mexican side (CONAGUA, 2010b; Hawley et al., 2000). Aquifer delineation between U.S. and Mexico does not coincide (see Fig. 4). For New Mexico, the Mimbres Aquifer basin includes seven sub-basins: Aquifers 20 and 21, and depending on the methodology, five other *associated basins* that include the Palomas–Guadalupe Victoria Aquifer (a non-bordering aquifer) located south of Aquifers 20 and 21, as well as the basin of Laguna de los Muertos, which is considered part of Aquifer 22 (Conejos-Medanos) in Mexico (Hawley et al., 2000).

The association of aquifers in this region is mainly related to groundwater flow connections that are not well understood considering the combination of confined and unconfined areas along the basin (DBSandA, 2005). Generally, groundwater flows from the north part of the basin, where the headwater of the Mimbres River is located and where most of recharge occurs from precipitation, toward the south into an endorheic basin near Deming, New Mexico and then vanishes into Mexico. Although the Mimbres River disappears before it reaches the border area, groundwater and storm drainage continues flowing southward into Mexico, recharging the closed basins of Aquifers 20 and 21, until it discharges into Laguna de Polvaredones overlaying Aquifer 20 (CONAGUA, 2010a, 2010b). The regional sink of the southern part of the Mimbres basin eventually discharges into Bolson de los Muertos to the south east of the basin (Hawley et al., 2000). Reversal of groundwater flow direction toward the north into New Mexico has been observed in the vicinity of Columbus, New Mexico, due to over-pumping (Hawley et al., 2000). Aquifer 20 receives groundwater flow from Aquifer 21 and the Palomas–Guadalupe Victoria Aquifer. Several cones of depression have been identified in the Mexican side near the edge of Aquifer 21 due to overpumping for agricultural use. Additionally, some groundwater has been recorded to flow north to New Mexico and to the west into the Palomas–Guadalupe Victoria Aquifer (CONAGUA, 2010a, 2010b). The main water issue in the region is overpumping, primarily in the U.S. side, where groundwater use is greater than annual recharge (Hawley et al., 2000). Water quality concerns are also concentrated in the border area around Deming and the Columbus–Palomas region. High levels of salinity and TDS and have been reported in the region mostly related to mining activities and mineral processing (Hawley et al., 2000).

3.5. Aquifers in the Chihuahua–New Mexico–Texas Region

The *Conejos-Medanos*/Mesilla-Bolson Aquifer (**Aquifer 22**) is a very well-studied and recognized transboundary aquifer. It is the third aquifer assessed under the TAAP initiative and is also included in the ISARM inventory (Puri and Aureli, 2009). It is the second-most studied aquifer in the entire Mexico–U.S. border region (primarily in the U.S. side) after the Valle de Juarez–Hueco Bolson Transboundary Aquifer (Aquifer 23). Although a variety of studies address this area as the Mesilla-Hueco Transboundary Aquifer, thereby including both aquifers 22 and 23 as part of the same system, there is actually very little water flowing between them (George et al., 2011) and they are divided by aquitards and geological faults. The commonality among these aquifers is mostly related to the intensive groundwater dependency of the growing El Paso–Ciudad Juarez populations. However, they do have important differences that will be addressed separately below.

Data regarding the boundaries of Aquifer 22 are not consistent. According to ISARM's description, this aquifer extends between Chihuahua and Texas, but there is a negligible mention of the almost 40% that is reaches into New Mexico. Likewise, the extent of the boundaries are not conclusive in the northern part of the aquifer basin (Chavez-Guillen and Klein, 2007). In contrast, there is reasonable amount of data recognizing the transboundary and interstate nature of this aquifer among Chihuahua, Texas, and New Mexico, with Texas having the smallest share in the western extreme of the state (around 10%) (see Fig. 4) (Chavez, 2000; Hawley et al., 2001; Salas-Plata Mendoza, 2006; Sheng et al., 2013). The aquifer is located in a very arid region where precipitation rarely exceeds 100 mm per year. It is considered an alluvial aquifer with the largest storage capacity in the region, from which some of the water discharges into the Rio Grande/Bravo River, but most is lost through evaporation of irrigated crops and through municipal and industrial use. Recharge sources are still uncertain but it is assumed to be small due to low precipitation and likely related primarily to irrigation seepage (Chavez-Guillen and Klein, 2007; TWDB and NMWRRI, 1997). In this region, where the Rio Grande/Bravo River reaches the entrance of the Mesilla Valley, the river becomes the boundary between Mexico and the United States and the main hydrological component of the region all the way to the Gulf of Mexico.

Aquifer 22 is considered to be in a developing stage on the Mexican side with some use in the Conejos-Medanos area; on U.S. side, the aquifer has been the primary source of water for the growing city of Las Cruces, New Mexico, and provides close to 20% of the water supply for the City of El Paso, Texas (Evans, 2006). The relevance of Aquifer 22 for TAAP, ISARM, Mexico, and Texas relates to its rechargeable capacity, which has already been considered for purposes of artificial recharge projects, particularly on the Mexican side. Given the pressures on the Valle de Juarez/Hueco Bolson Aquifer (Aquifer 23) from mining activities, rising salinity levels, and growing water demand, Aquifer 22 can be a valuable alternative groundwater source in the region (CONAGUA, 2009g; Hathaway, 2011). La Mesilla Aquifer in New Mexico a component of Aquifer 22, has pumping restrictions and has developed strict conservation programs (Darcy, 2012). Moreover, groundwater contamination is a major concern in this area due to cropping and high density of septic systems (TWDB and NMWRRI, 1997). In contrast, there are no major pumping restrictions on the portions of Aquifer 22 found in Chihuahua or Texas, and Mexico has not reported a deficit on the Conejos-Medanos aquifer (CONAGUA, 2009g).

Aquifer 23, the *Valle de Juarez*/Hueco Bolson Aquifer, is the most studied and significant transboundary aquifers between Mexico and the U.S. Extensive research on water conditions and management challenges are documented, as well as concerns related to future water availability in the region where the 2 million people inhabit the sister cities of El Paso and Ciudad Juarez (Hathaway, 2011). Aquifer 23 is recognized as transboundary by Texas, New Mexico and Chihuahua, is the fourth aquifer assessed under TAAP, and is part of the ISARM inventory. Boundaries are relatively consistent among the literature, however, some studies include the Tularosa Aquifer in New Mexico (see Fig. 4) as part of the Hueco Bolson Aquifer because of groundwater flow from the Tularosa to the Hueco Bolson Aquifer. Inclusion of the Tularosa Aquifer basin as part of the Hueco Bolson system seems to be related to those assessments addressing interstate hydrological groundwater flow between New Mexico and Texas. However, this perspective is not as common in international groundwater assessments between Mexico and the U.S. (Puri and Aureli, 2009; Sheng et al., 2013; TWDB and NMWRRI, 1997). In fact, the small stretch in the north-west part of Hueco-Bolson Aquifer, which is located in New Mexico, is not always recognized at international level as New Mexico's transboundary share of the aquifer (Chavez-Guillen and Klein, 2007). See Fig. 4.

Aquifer 23 is one of the largest aquifers in the border region and is nearly 3000 m thick. The aquifer has provided water to El Paso, Texas, Dona Ana County in New Mexico, and Ciudad Juarez in Chihuahua, Mexico for decades. Historically, recharge came mostly from precipitation and agricultural runoff and discharge flowed into the Rio Grande. However, as overexploitation began to affect groundwater flows, the river has become a losing stream, recharging the aquifer and diminishing surface water flow (Chavez-Guillen and Klein, 2007; George et al., 2011).

While El Paso has secured alternative surface water resources, implemented strict conservation programs, and constructed one of the largest inland desalination plant in the world (Hathaway, 2011), Ciudad Juarez, some communities in New Mexico and the Fort Bliss Military Reservation still depend 100% on the region's groundwater (Sheng et al., 2013). High salinity levels due to over-pumping and agricultural drainage in the Mexican side has challenged the water quality of the aquifer. Additionally, since the Rio Grande now recharges the aquifer, concern has grown over discharges of Ciudad Juarez sewage into the Rio Grande main stem without treatment (Chavez, 2000; Mumme, 2000). Mexico has reported TDS concentrations of 1200 and 3000 ppm in the urban area of Ciudad Juarez (CONAGUA, 2009i). Though some research based on current pumping rates and population growth in the area have estimated the depletion of the aquifer by the year 2025 (Evans, 2006), more recent studies have been able to report an aquifer lifespan of more than 50 years considering the recent conservation strategies implemented and water quality technology development in the region (Boghici, 2011; El Paso Water Utilities (EPWU); U.S. Army Corps of Engineers, 2009).

3.6. Aquifers in the Chihuahua–Texas region

Aquifer 24 is the *Valle del Peso* Aquifer bordering the West Texas Bolsons Aquifer in the U.S. side. This is a poorly studied aquifer both in Texas and Chihuahua (CONAGUA, 2011b; Mace, 2001). It has not been technically or officially identified as transboundary, however, some literature has referenced this aquifer as transboundary (Mumme, 2000). Fig. 5 shows the extent and geography of the bolsons on the U.S. side, which are bounded by igneous material that is equally present in the geology of the aquifer on the other side of the river (Fisher, 2015; Hoel, 2013; NMWRRI, 2002; NWS, 1999, 2014; TWDB, 2006). On the Mexican side, Aquifer 24 is considered a limited storage capacity aquifer with low permeability and no major hydrological components. Recharge comes from precipitation runoff from surrounding mountains and the aquifer discharges into the main stem of the Rio Grande River (CONAGUA, 2011b).

Aquifer 25, the *Bajo Rio Conchos*, also borders a tiny section of the extreme south of the West Texas Bolson aquifer in the U.S. side, but there is no available data that suggests any transboundary linkages and research on groundwater conditions in the area have not been conducted (CONAGUA, 2010g). Data on Aquifer 25 is very limited but suggests an alluvial composition in the south-center part of the aquifer and igneous sediment constituting the boundaries of the system. The aquifer is believed eventually to discharge into the Rio Grande (CONAGUA, 2010g). The main uses for groundwater in this area include livestock and meeting some municipal needs for the cities of Ojinaga and Guadalupe in Chihuahua. In Texas, groundwater is mainly used for irrigation and livestock, but also for the cities of Presidio (Ojinaga's sister city), Sierra

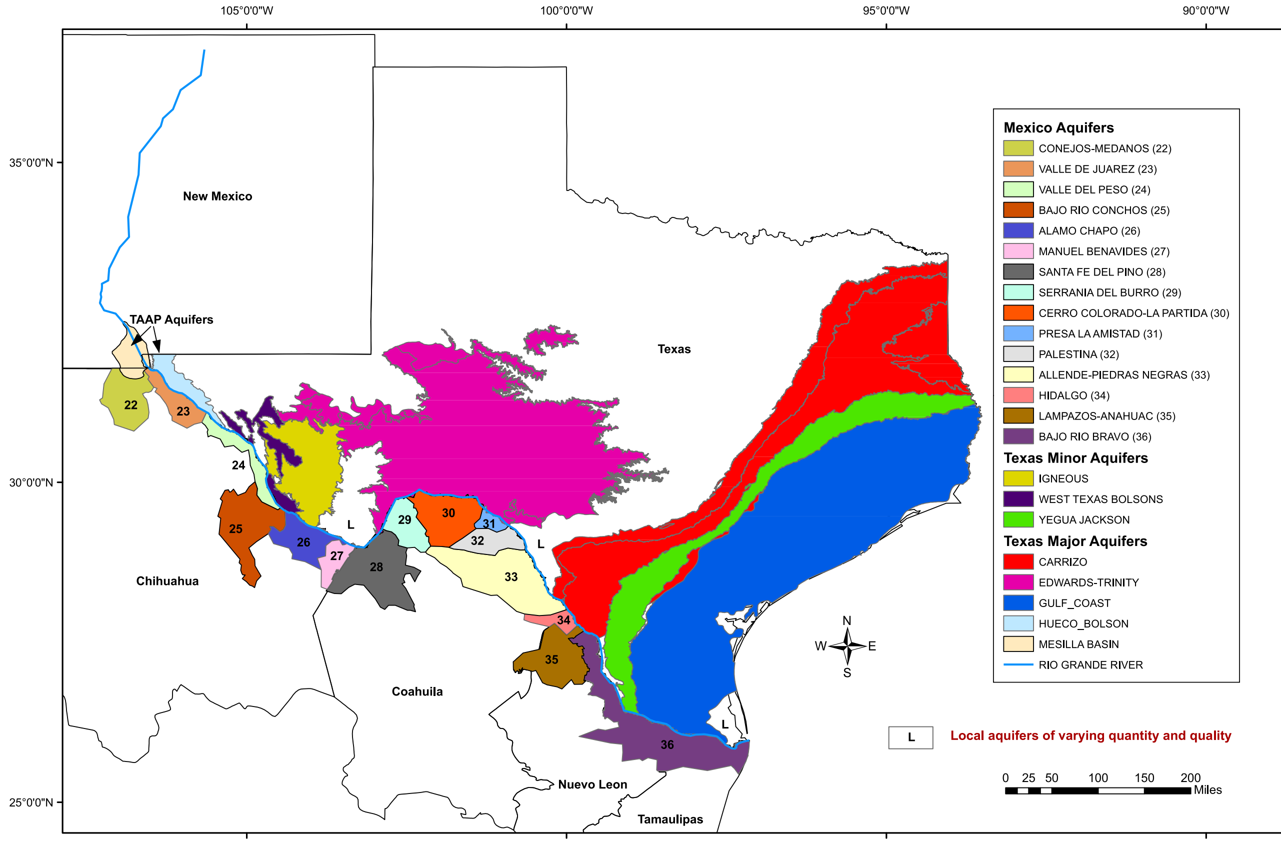


Fig. 5. Chihuahua–Coahuila–Nuevo Leon–Tamaulipas–Texas aquifer/basins.

Blanca, Valentina, and Van Horn. There is some indication that groundwater levels have declined over the last 50 years, mostly in the area of Van Horn and in the Wild Horse basin area (George et al., 2011). There is no reported deficit for Aquifers 24 nor 25 in the Mexican side.

Aquifer 26 is the *Alamo Chapo* Aquifer/Igneous Aquifer. Just as for Aquifers 24 and 25, there is limited information regarding the transboundary nature of this aquifer. On the U.S. side, the igneous composition of this region makes it a very complex system in which different sub-aquifers are compartmentalized and their interconnections are not completely understood (Mace, 2001). See Fig. 5. Data from the U.S. denotes recharge into the aquifer from precipitation and losing streams in volumes higher than natural discharge, which occurs through springs in the mountain areas. The aquifer has substantial storage capacity and has been considered in plans for future water needs projects in the El Paso region (George et al., 2011). Groundwater in the region is used mainly to meet municipal needs in the cities of Alpine, Fort Davis and Marga, as well as for some agriculture production. There have been no significant water level declines on the U.S. side (George et al., 2011). On the Mexican side, there are no major communities dependent on this aquifer and there is practically no urban development in the region. Additionally, there is no information on groundwater flow and no report of a groundwater deficit (CONAGUA, 2010f).

The last aquifer located in Chihuahua is **Aquifer 27**, named *Manuel Benavides*, which borders an area in Texas that has no officially recognized aquifer. However, one study suggests the presence of *local aquifers* on the Texas side, but with no defined boundaries and negligent water storage. No additional research has been conducted in this area (George et al., 2011). On the Mexican side, except for the alluvial material concentrated in northern part of the aquifer along the border with Texas, just as its neighbor's aquifers to the west, limited data conditions prevail. No deficit or major groundwater development in the area is reported (CONAGUA, 2010h). Due to the limited data on both sides of the border, Aquifer 27 cannot yet be characterized as transboundary.

3.7. Aquifers in the Coahuila–Texas region

Aquifer 28, the *Santa Fe del Pino* Aquifer, borders the same general area in Texas as Aquifer 27. While there is limited data as far as the transboundary component of this aquifer, there are important elements worth mentioning. This area occupies the northern part of the city of Ocampo and, to a smaller extent, the cities of Acuna, Muzquiz, San Buenaventura, and Sierra Mojada. Groundwater is mostly used to supply municipal needs, but groundwater development in the region is still in an early stage (CONAGUA, 2011c). Recharge comes mainly from precipitation, however, the aquifer does not have much infiltration capacity or transmisivity. The aquifer discharges into the Rio Grande River as well as to some springs in the northern part of the aquifer where the Maderas del Carmen National Park Protected Area in Coahuila borders the Big Bend National Park in Texas (CONAGUA, 2011c). Salinity issues have been reported in the area with TDS levels ranging between 220 and 4900 ppm, and no deficit has been reported (CONAGUA, 2011c).

The region covered by Aquifers 24, 25, 26, 27 and 28 is a very arid-desert environment with low density population, limited access to surface water, and highly dependency on groundwater for all uses. Therefore, intensive development of groundwater, both in Mexico and the U.S., has impacted the wetland ecosystems (*cienegas*) that prevail in this area highly dependent on groundwater for its sustainability. According to data from Texas, this is one of the most negatively impacted habitats in the state with approximately half of the native fishes of the Chihuahuan Desert being either in danger of extinction or already extinct (Garret and Edwards, 2001). So far, there is not enough data to assume any possible groundwater linkages. However, environmentally and ecologically speaking, wetland ecosystems in this region are in fact interconnected and highly dependent on groundwater for their subsistence.

Aquifer 29 is generally referred to as the Edwards-Trinity-Burro Aquifer. It is recognized by ISARM and Mexico as a transboundary aquifer system. The transboundary nature of at least part of this aquifer is also recognized by the State of Texas (Boghici, 2002; Chavez-Guillen and Klein, 2007; CONAGUA, 2014).The boundaries of this aquifer, however, are not well defined or consistent, and might include multiple aquifers in both sides of the border. Texas defines the boundaries of this aquifer by geological features, which can contain an aquifer or multiple interconnected aquifers. In this case, the Edwards in the Balcones fault and the Edwards-Trinity (Plateau) may also be included as part of the system. On the Mexican side, the specifics about which aquifers could be part of this system are not definitive as the aquifer system has yet to be completely studied (Boghici, 2002). The extent of the aquifer basin varies from 47,000 km^2 to 70,000 km^2, depending on the literature (Boghici, 2002; Chavez-Guillen and Klein, 2007). Based on the limited data available for the Edwards Aquifer boundaries in the Mexican side, at least three aquifers can be identified as potentially transboundary with the Edwards-Trinity. **Aquifer 29** (*Serrania del Burro*) **and Aquifer 30** (*Cerro Colorado-La Partida*) in the northwestern part of the State of Coahuila, and **Aquifer 31** (*Presa La Amistad*) in the northeastern part of the state (CONAGUA, 2014; IGRAC, 2014). See Fig. 5.

The main groundwater bearing units of this aquifer are located in northern Coahuila around the Serrania del Burro Mountains (West Nueces, McKnight and Salmon Peak formations) where the aquifer partially discharges as natural springs, which in turn serve as sources of groundwater recharge for local shallow aquifers connected to the Rio Grande River (Boghici, 2002). Irrigation districts, small and medium sized communities, and the sisters cities of Ciudad Acuna (Coahuila) and Del Rio (Texas) are primarily dependent on this aquifer for their water supplies (Chavez-Guillen and Klein, 2007; Mumme, 2000). However, the hydrogeological data on this aquifer is limited in both Mexico and the U.S. According to Mexican studies, groundwater development is limited in this region (Aquifers 29, 30 and 31) and no deficit has been reported (CONAGUA, 2011d, 2011e; 2011h). In Texas, there has been more groundwater development in the area, mostly for irrigation in Uvalde, Edwards, Kinney, and Val Verde counties, which border directly Aquifer 31 (Presa La Amistad) in Mexico. That aquifer discharges around 10 h m^3 of groundwater into Amistad Reservoir through groundwater flow. This amount is accounted to fulfill the 1944 treaty surface water requirements with Texas before discharging to the Rio Grande (CONAGUA, 2011h). This area reports high levels of transmisivity along the border area in the Mexican side as well as groundwater confinement that increases well yields south of Ciudad Acuna and near Amistad Reservoir (Boghici, 2002; George et al., 2011). There is data that reports groundwater flows generally from the highlands in Coahuila (the Serrania del Burro Mountains) toward Amistad Dam and the Rio Grande, feeding rivers such as Devils, Sycamore and Nueces in Texas, and Arroyo Las Vacas, Rio San Diego, Rio San Rodrigo and Rio Escondido in Coahuila. But pumping and drainage conditions seemed to have modified the regional pattern and a mild cone of depression has reversed the hydraulic gradient northeast of Uvalde city (Boghici, 2002).

The area overlying Aquifer 29 is considered an ecological priority region in the state of Coahuila, because it hosts the headwaters of all perennial rivers in the state. The headwaters of the San Rodrigo and San Diego rivers are interconnected to the Five-Springs Region (*region de los Cinco Manantiales*), which provides water to the cities of Ocampo, Muzquiz, and Cuatrocienegas (CONAGUA, 2011d). There is no reliable data on groundwater development in Aquifer 29, but it is estimated to be negligible and mostly used for municipal supplies. The most relevant hydrological component of this aquifer is that groundwater discharges mainly as natural springs throughout the northern part of the State of Coahuila before it eventually reaches the Rio Grande River. Even though ISARM and CONAGUA recognize the transboundary nature of this aquifer system, there are some annotations about the formations on both sides of the border that discharge eventually in the Rio Grande without any underground water circulation among them (Puri and Aureli, 2009). As for Aquifer 30, data reported from Mexico shows low groundwater availability of around 6 h m^3 per year with no major rivers or springs in the region. Low infiltration from precipitation has also been recorded, mostly located in the southern part of the aquifer (CONAGUA, 2011e).

Water quality in this aquifer system is predominantly fresh, however, wells drilled near the limiting line or the downdip interface of the aquifer, which is considered the ''bad water zone'' (brackish water), shows TDS between 1000 and 3000 mg/l (Boghici, 2002). Moving south-east of this ''bad water zone'' mineralization of the groundwater increases (Ashworth and Hopkins, 1995).

Based on available data there is reasonable confidence to suggest that Aquifer 31 (Presa La Amistad) is a transboundary aquifer. Boundary delineation problems and lack of data do not allow a conclusive determination of the transboundary nature of Aquifers 29 and 30. Because Texas utilizes geological boundaries to delineate aquifer limits, whereas Mexico and the rest of the states in the U.S. use either a combination of true and/or basin boundary methodology, the transboundary aquifer puzzle is even more challenging along the Texas border.

Aquifer 32 is the *Palestina* Aquifer basin in Mexico, which borders another series of *local aquifers* in Texas. There is no international, national, or state data that characterize this aquifer as transboundary. There is no technical information on the Mexican side about the hydrological conditions of this aquifer, except that it does not show a water deficit or groundwater flow toward any of the surrounding water bodies (CONAGUA, 2011f). There is an irrigation district located in this region, but there is little data on the proportion of surface and groundwater used for irrigation. Some literature, however, suggests that the Carrizo Wilcox Aquifer in Texas may extend from Amistad Dam to Falcon Dam and thereby border Aquifer 32 (Mumme, 2000) Nevertheless, according to data from the Texas Water Development Board (TWDB), the Palestina Aquifer does not reach the Carrizo Wilcox Aquifer (George et al., 2011). See Fig. 5. Other studies suggest that Aquifer 32 could be interconnected to Aquifer 31 (Presa La Amistad) through the surface and groundwater conveyance and reservoir system used to comply with the US–Mexico 1944 treaty (Danner et al., 2006), however, there is no conclusive data on this premise.

Aquifer 33 is the *Allende-Piedras Negras* which borders what the State of Texas defines as *Local aquifers.* There is reasonable data to confirm the transboundary relationship of this aquifer, however, it has not received official recognition in Mexico or the U.S. or by ISARM. Official reports of the TWDB show no identifiable aquifer in this area. However, technical assessments that address specific transboundary study areas in Texas have identified and studied the transboundary linkages of Aquifer 33 (Boghici, 2002). As with the other aquifers in the region, the boundaries identified by Mexico do not coincide with the boundaries presented in TWDB technical studies (CONAGUA, 2011a).

According to technical assessments, of the 7136 km^2 of the aquifer area, about 75% is located in Mexico (Boghici, 2002). The main cities found in the region are Allende, Villa Union, Morelos, Zaragoza, and Nava Guerrero in the Mexican side, and Brackettville and Spofford in the U.S., while the largest urban center is the Piedras Negras–Eagle Pass sister cities area. Groundwater discharges from both sides of the border flowing into the Rio Grande and Rio Escondido alluvial areas, which are the main gaining rivers in the system, and also as spring flows that drains the aquifer basin (Boghici, 2002). Recharge occurs from precipitation at high elevations in Serrania del Burro and Lomerio Peyotes Mountain areas in the Mexican side where the Escondido and San Rodrigo rivers originate, as well as from major springs and irrigation seepage (CONAGUA, 2011a). Some data suggests the geochemical interconnection of Aquifer 33 with the Edwards-Trinity Aquifer as groundwater flows from the Edwards Aquifer recharge Aquifer 33 in the Peyotes area in Mexico (Batzner, 1976). However, there is no conclusive data for this relationship.

Groundwater on the Mexican side is mainly used for mining activities (MICARE coal mine), energy generation by the National Electric Commission, and agriculture and municipal purposes (Boghici, 2002; CONAGUA, 2011a). Intensive groundwater development for irrigation and municipal use has been recorded in Texas (60% and 40%, respectively) (George et al., 2011). Both mining activity in the Mexican side and irrigation on the U.S. side have demonstrated the sensitivity of groundwater flows in the system, as well as storage depletion, all of which have had a negative effect on ecosystems dependent on spring flows (Rodriguez-Martinez, 2000). Near Piedras Negras Valley, groundwater has been declining, particularly in the dewatering operations area of the Micare coal mine (Gutierrez-Ojeda et al., 2013). In contrast, in the area north of Zaragoza City between Nava and Villa Union, water levels have been increasing (Boghici, 2002; CONAGUA, 2011a). On the Mexican side there is no deficit reported in Aquifer 33 (CONAGUA, 2011a).

3.8. Aquifers in the Coahuila–Nuevo Leon–Tamaulipas–Texas Region

Aquifers 34, 35 and 36 – *Hidalgo* Aquifer (Coahuila), *Lampazos-Anahuac* Aquifer (Nuevo Leon) and the western part of *Bajo Rio Bravo* Aquifer (Tamaulipas), respectively **–** are hydraulically linked to the Carrizo Wilcox Aquifer in Texas. At the same time, Aquifer 36 is also connected to the Yegua Jackson and Gulf Coast aquifers in Texas. Because this is a very complex hydrological environment and aquifer boundaries are not well defined or understood, the aquifer characteristics will be addressed both as part of the same system, and separately considering their delimitation differences and particular characteristics. See Fig. 5.

The total extension of the Carrizo Wilcox Aquifer in Texas and Mexico is 17,500 km^2, of which 14,200 km^2 lies under Maverick, Dimmit, Uvalde, La Salle, Zavala, and Webb counties in Texas, and 3300 km^2 within the Mexican States of Coahuila, Nuevo Leon, and Tamaulipas (Boghici, 2002). The boundaries and limits of the aquifers in the Mexican side do not coincide with the ones found in technical studies from the U.S. side. According to the TWDB, the Carrizo Wilcox Aquifer is bounded by geological limits that extends into Louisiana and Arkansas toward northeastern Texas, and into Coahuila, Nuevo Leon, and Tamaulipas in Mexico (Boghici, 2002). The area covered by Carrizo Wilcox includes the complete area identified as Aquifer 34 (Hidalgo), Aquifer 35 (Lampazos-Anahuac), and the western side of Aquifer 36 (Bajo Rio Bravo) in the Mexico side. Of the three aquifers in Mexico that are linked to the Carrizo Wilcox in Texas, only Aquifer 36 is recognized as transboundary by ISARM and Mexico though there is indication that the system might extend up to Aquifer 34 in Mexico (Chavez-Guillen and Klein, 2007; CONAGUA, 2014). In contrast, technical studies of the TWDB regard Aquifers 34 and 35 as transboundary with the Carrizo Wilcox Aquifer (Boghici, 2002). The extent of the Carrizo Wilcox aquifer limits into Mexico are not well defined. Based on available data, it is reasonable to confirm the transboundary nature of Aquifer 36 which hosts the sister cities of Laredo-Nuevo Laredo, with the Carrizo Wilcox and Gulf Coast aquifers. Moreover, there is some indication of the transboundary relationship of Aquifers 34 and 35 with the Carrizo Wilcox Aquifer, but there is no data about the transboundary nature of Aquifer 36 with the Yegua Aquifer in Texas. See Fig. 5.

There is data on stream and groundwater linkages between **Aquifer 34** and Carrizo Wilcox and important levels of transmissivity in the southern part of aquifer (Boghici, 2002). No major groundwater development has been reported in the small community of Hidalgo (1516 inhabitants) where Aquifer 34 is located, and there are no major tributaries to the Rio Grande or groundwater flow to adjacent aquifers or water bodies (Danner et al., 2006). In addition, there has been no deficit reported in the Mexican side (CONAGUA, 2011g). Recharge of the Carrizo Wilcox Aquifer occurs primarily from direct infiltration of precipitation, losing streams, and discharges mainly from irrigation operations in the Winter Garden Area in Texas, which constitutes around 60% of groundwater use in the region (Boghici, 2002; George et al., 2011). Groundwater quality in this region is moderately saline and supplies late winter irrigation for vegetable production in Dimmit, Zavala, and eastern Maverick counties. Higher salinity levels have been reported in Aquifer 34 on the Mexican side ranging from 482 mg/l to 9334 mg/l (Boghici, 2002; CONAGUA, 2011g). Groundwater levels have declined on the U.S. side and heavy pumping along the Nueces River around Crystal City and Cotulla have caused reversal of groundwater flows (Boghici, 2002).

As for **Aquifer 35**, there is not much data to confirm transboundary elements from the Mexican side, however, it has some important hydrological features worth mentioning. The Rio Salado, which is one of the most important tributaries to the Rio Grande River, flows from west to northeast draining the aquifer basin before it discharges into the main stream of the Rio Grande. Groundwater in this area discharges around 19 h m^3 per year into Rio Salado, which is greater than the groundwater development in the area (3.36 h m^3 per year) (CONAGUA, 2011i). The potential transboundary element of this aquifer, regardless of the tiny stretch that borders Texas, relies on the groundwater flow that is accounted in the total volume of surface water shared between Mexico and Texas according to the 1944 U.S.–Mexico treaty (CONAGUA, 2011i; Danner et al., 2006).

In the Mexican region of **Aquifer 36**, irrigated agriculture dominates groundwater use followed by municipal and industrial uses. It hosts the largest sister cities of the region: Laredo–Nuevo Laredo. The most productive groundwater is located around the cities of Reynosa and Matamoros and the best water quality is located along the channel of the Rio Grande River (CONAGUA, 2009f). Several cones of depression in the city of Reynosa have been reported as well as reversal of groundwater flows toward the north due to over-pumping in Texas (Gulf Coast Aquifer) (CONAGUA, 2009f). The transboundary linkages have also been recorded in terms of water quality as both sides report salinity levels that exceed U.S. standards in about 50% of the wells (Mumme, 2000). Groundwater contamination, due to sewage disposal by Mexican cities and industrial wastes from *maquiladoras* into the main stem of the Rio Grande River has also contributed to degraded groundwater quality (Mumme, 1988; Mumme, 2000). Even though there is no overall groundwater deficit reported by Mexico for Aquifer 36, groundwater levels have been declining, especially in areas were good water quality is available (mostly urban areas), showing a deficit of around 0.6 Mm^3 per year (CONAGUA, 2009f).

On the U.S. side, the Gulf Coast Aquifer is used for municipal, industrial, and irrigation purposes. Excessive pumping and water level declines of as much as 100 m has led to land subsidence issues in the Texas counties of Harris, Galveston, Fort Bend, Jasper, and Wharton (George et al., 2011).

The main groundwater challenges affecting Aquifers 34 through 36 are related to water quality and high salinity levels (brackish water). Except for some areas around the cities of Reynosa, Matamoros, and Nuevo Laredo in Mexico, and Laredo in Texas, groundwater quality in all three aquifers exceeds 1000 TDS m/l, while TDS in much of Aquifer 36 ranges between 600 mg/l and 11,000 m/l (CONAGUA, 2009f). The salinity in this region is related to the geologic faults of the Burgos Basin formation where gas and oil deposits are located. As a result, irrigation in this area is highly dependent on surface water from the Rio Grande River.

Fig. 6 maps the complete puzzle of aquifers in the border region between Mexico and the United States based on available data (ASLD, 1993; CDWR, 2003; CESAR, 2000; Fisher, 2015; Hoel, 2013; Megdal and Scott, 2011b; NMWRRI, 2002; NWS, 1999, 2014; TWDB, 2006). Fig. 7 shows the map with their corresponding level of confidence of their transboundary nature.

4. The challenge of definition, principles, and criteria

One of the challenges in delineating transboundary aquifers is the lack of consistency in defining an aquifer among institutions, nations, and the international community.

For example, while the term aquifer is not defined in the Water Code of the State of Texas, it is defined in that state's Administrative Code (§§330.3(8) and 335.1(8)) in the context of municipal and industrial solid waste management as "[a] geological formation, group of formations, or portion of a formation capable of yielding significant quantities of groundwater to wells or springs." Under this definition, the formation must yield a "significant" volume of water in order to be classified as an aquifer. However, the absence of language defining the physical boundaries of an aquifer makes it challenging to delineate such formation on a map. It is noteworthy that the Texas Water Code (§§ 35.002(6) and 36.001(6)) does define "groundwater reservoir" as a "specific subsurface water-bearing reservoir having ascertainable boundaries containing groundwater." Whether "groundwater reservoir" is equivalent to "aquifer" is unclear.

In contrast, Mexico defines an aquifer as "*any geological formation or set of geological formations that are hydraulically connected among themselves, with circulate or stored groundwater which can be extracted for sustainable exploitation, and whose lateral and vertical limits are defined conventionally for purposes of assessment and management of groundwaters*" (DOF, 2011). By this definition, it is not required to have significant quantities of water in order to be considered as aquifer. However, the boundaries are somehow determined administratively rather than scientifically in relation to the physical and managerial considerations of each aquifer.

At the international level, apart from the 1997 UN Convention on the Law of the Non-navigational Uses of International Watercourses, there is no international legal instrument that governs transboundary aquifers *per se*. Moreover, there is no global standard on the definition of what constitutes a transboundary aquifer, or on principles and criteria for transboundary groundwater delimitation, protection, and management practices (Robins and Fergusson, 2014). The 1997 UN Convention, which went into force in August 2014, provides principles and norms for managing transboundary rivers and lakes and applies to transboundary aquifers to

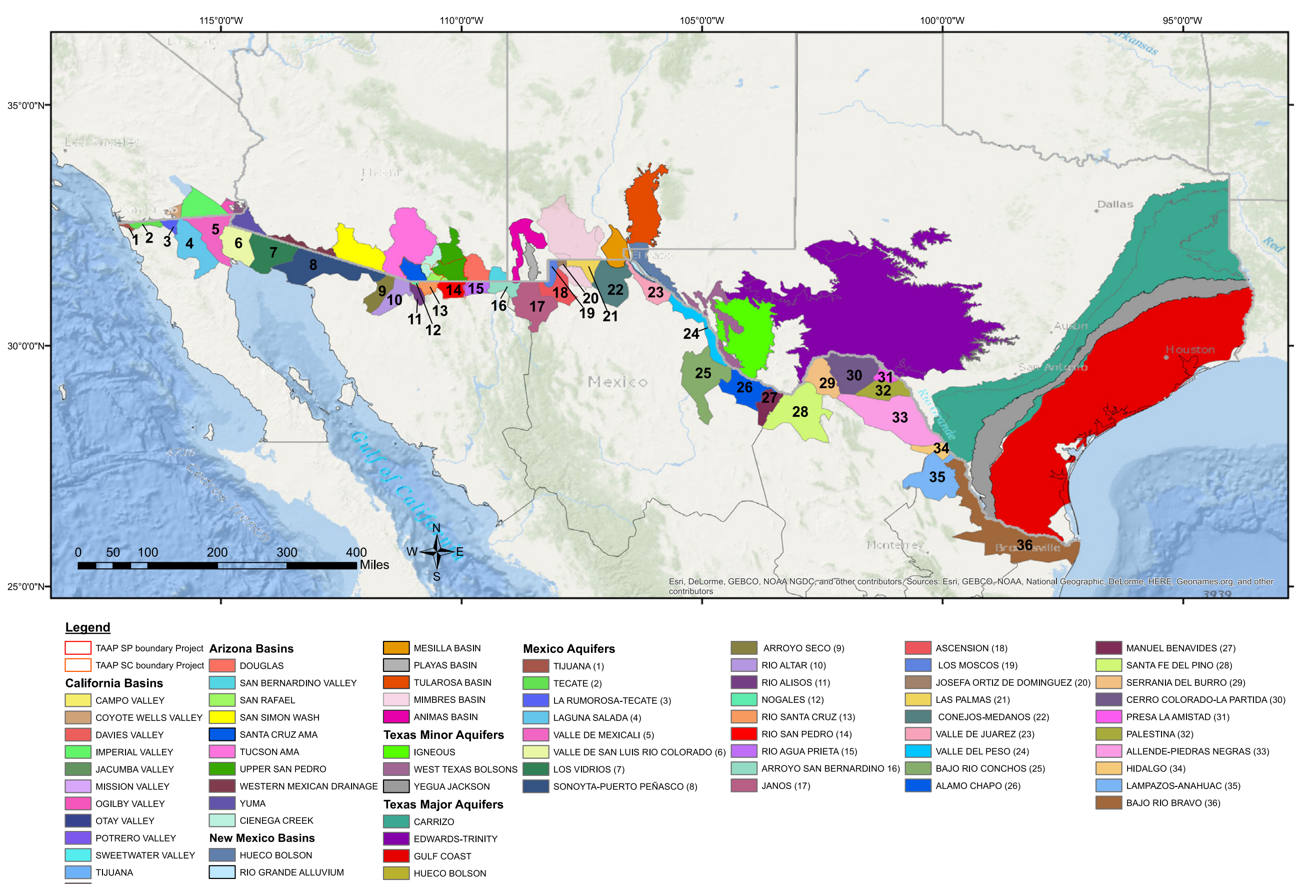
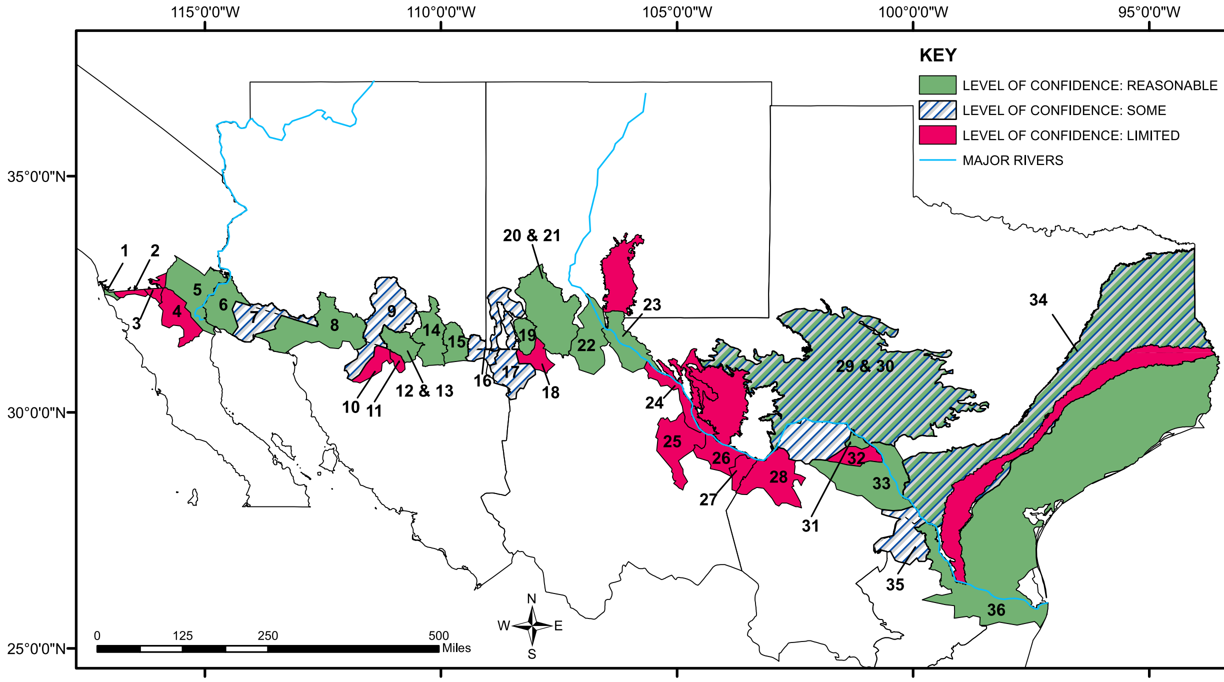


Fig. 6. Mexico–US categorization of border aquifer/basins.



16 Confidence Level: Reasonable

(1) Tijuana/San Diego
-(Tijuana, Otay Sweetwater and Mission system)
(5) Cuenca Baja del Rio Colorado system:
Valle de Mexicali/ Imperial, Ogilby and Yuma Valley
(6) Cuenca Baja del Rio Colorado system:
Valle San Luis Rio Colorado/Yuma
(8) Sonoyta-Papagos system:
Sonoyta-Papagos/San Simon Wash
(12) Nogales/Santa Cruz (TAAP1)
(13) Santa Cruz/Santa Cruz-San Rafael (TAAP1)
(14) San Pedro/San Pedro (TAAP2)
(15) Rio Agua Prieta/Douglas (INA)
(19) Los Moscos/ Hachita Moscos
(20) Josefa Ortiz de Dominguez/Mimbres
(21) Las Palmas/Mimbres
(22) Conejos Medanos/Mesilla Bolson (TAAP3)
(23) Valle de Juarez/Hueco Bolson (TAAP4)
(31) Presa La Amistad/Edwards
(33) Allende-Piedras Negras/Local aquifers
(36) Bajo Rio Bravo/Carrizo Wilcox-Gulf Coast
(Yegua Jackson no data)

8 Confidence Level: Some

(7) Los Vidrios/Western Mexican Drainage
(9) Arroyo Seco/Tuscon AMA
(16) Arroyo San Bernardino/San Bernardino Valley
-San Bernardino basin
(17) Janos/Animas and Playas aquifer basin
(29) Serrania del Burro/Edwards
(30) Cerro Colorado-La Partida/Edwards
(34) Hidalgo/Carrizo Wilcox
(35) Lampazos/Anahuac-Carrizo Wilcox

12 Confidence Level: Limited

(2) Tecate/Potrero Valley and Campo Valley
(3) La Rumorosa-Tecate/Jacumba Valley and Davies Valley
(4) Laguna Salada/Coyote Wells Valley
(10) Rio Altar/Tucson Active Management Area
(11) Rio Alisos/Santa Cruz
(18) Ascencion/ Hachita Moscos
(24) Valle del Peso/West Texas Bolsons
(25) Bajo Rio Conchos/West Texas Bolsons
(26) Alamo Chapo/Igneous
(27) Manuel Benavides/Local aquifers
(28) Santa Fe del Pino/Local aquifers
(32) Palestina/Local aquifers

Fig. 7. Confidence level of the transboundary nature of aquifers/basins between Mexico and the United States.

the extent that those water bodies are interrelated to transboundary surface waters. Under the Convention, a watercourse means a "*system of surface waters and groundwaters constituting by virtue of their physical relationship a unitary whole and normally flowing into a common terminus*". While the inclusion of groundwater within the scope of the Convention is a progressive achievement in international law, the definition of watercourse excludes some important groundwater resources. It effectively excepts aquifers related to a surface waterbody, but which flow to a different terminus, transboundary aquifers that might be linked to a domestic river but not one that is internationally transboundary, and solitary aquifers that are not part of a system of surface and groundwaters, such as fossil aquifers (Eckstein, 2005). Of the aquifers on the Mexico–U.S. border, Aquifers 17, 18, and 19 might fall into this gap as they traverse the highly arid border between Chihuahua and New Mexico where surface water is limited and poorly connected to groundwater. Given the lack of information about many of the other aquifers on the border, it is possible that others also could be excluded from the scope of the Convention.

In recent years, however, a number of important developments have emerged with regard to regulations applicable to communication, data exchange, criteria selection, and management of transboundary groundwater resources. For example, the European Union's 2000 Water Framework Directive and its 2006 daughter directive on groundwater established specific measures designed to ensure the quality and quantity of all aquifers, including transboundary aquifers (Eckstein, 2011b). The 1992 UNECE Convention on the Protection and Use of Transboundary Watercourses and International Lakes is more expansive and inclusive than the 1997 UN Watercourses Convention and applies to all transboundary aquifers in member nations. Moreover, a management agreement on the Genevese Aquifer, an arrangement with rudimentary extraction controls on the Al-Sag/Al-Disi Aquifer, and two data sharing arrangements in North Africa, were the world's first treaties specifically tailored to address issues pertaining to transboundary aquifers (Eckstein, 2011b). Potentially the most significant development, though, was the 2008 United Nations Draft Articles on Transboundary Aquifers, a series of international norms proposed by the UN International Law Commission for the UN General Assembly, including a definition of transboundary aquifer. While the Draft Articles are still under considerations, they have elevated transboundary groundwater resources to the highest levels of international law and relations (Eckstein, 2011b).

Apart from the concerns related to the aquifer definition, the above analysis evidenced important differences among the states and countries in defining aquifer boundaries. Texas for example, defines its aquifer boundaries according to geological features, which could contain more than one aquifer in the unit. The only exception to this approach is for Aquifers 22 and 23, which Texas demarcates by using true aquifer boundaries. In contrast, California uses basin boundaries and Arizona and New Mexico uses both basin and true aquifer boundaries, depending on the aquifer. In some other cases, regardless of the state, the aquifer boundaries are delimited by project-funding restrictions (Timmons, 2014). In the case of Mexico, data collection and methods are developed by one centralized agency, which generally uses a basin aquifer boundary methodology. The agency, however, occasionally also follows administrative boundaries depending on the jurisdiction of the Hydrological Basin Council (Randall, 2014). In addition, the resolution of the polygons in the shapefiles that represent these aquifers, as used in GIS analyses, varies among the countries. Mexico uses lower resolution polygons, which were enshrined in Mexican law in 2000, whereas the U.S. uses more updated higher resolution polygons (Callegary, 2014). This reality creates unique challenges when piecing together aquifers from both sides of the international border and significantly affects the quality of maps produced for analysis.

Another challenge emerging from the study is that, with the exception of aquifers researched through the TAAP and those located along New Mexico–Chihuahua border, all of the available studies depict border aquifers with a boundary that terminates at the border. In other words, research into a transboundary aquifer typically ends abruptly on the border line (Callegary, 2014). This reality is crucial for understanding the lack of comprehensive research in the Mexico–U.S. border region, the institutional weakness in promoting sustainable management practices, the uncertainty about the conditions of transboundary groundwater resources in the region, and the urgent need to revise the research and institutional agenda to address transboundary aquifers.

5. Conclusion

The dearth of knowledge about transboundary groundwater resources between Mexico and the U.S. is alarming. Water quality conditions, water availability, future demand, vulnerabilities, safe yield, and many other factors are unknown in most of the aquifers identified in the border region. In addition, joint institutional and management practices are nonexistent or poorly organized throughout the frontier. Except for the four aquifers studied under the TAAP, holistic or binational research on the border's aquifers is practically nonexistent.

The categorization developed by this study offers preliminary results on two important issues: where and how many transboundary aquifers potentially exist on the Mexico–U.S. border. The transboundary nature of these aquifers was identified based on available geological, social, and institutional data, with priority given to hydrological considerations. However, to develop a governance framework that manages the border-region's aquifers sustainably, there needs to be a common methodology for determining physical aquifer boundaries, as well as assessing the social, economic, political, environmental, legal, and institutional dimensions that are relevant to each aquifer. Moreover, the approach for determining the transboundary nature of aquifers requires standardization of criteria used by the riparians to efficiently assess management strategies at the transboundary level.

While we have partially answered our question of where and how many transboundary aquifers are shared between Mexico and the United States, we now face an even more important matter. Recognizing that there is no aquifer that ends abruptly on the border line, the basic premise is that potentially all aquifers are transboundary to some extent. But, to what extent and under what considerations are each aquifer transboundary? Understanding these questions and the implications of the possible answers will not only allow us to address the alarming data gaps at the physical level, but it will also settle the dispute between uniformity versus ad-hoc research and institutional approaches. It will offer us the possibility to derive the transboundary nature of an aquifer into a human-environmental relationship understandable and adjustable to its own institutional and physical framework, where management is not limited to water, but also encompasses social, economic, and political realities and challenges.

Acknowledgements

The authors are grateful to The National Science Foundation LSAMP BTD for financial support. The public data can be obtained through the referenced websites, and/or from Dr. Rosario Sanchez (rosario@tamu.edu), while the data the authors created is available from Dr. Sanchez. The authors wish to thank Timothy M. Ross at CA Department of Water Resources, Stacy S. Timmons at NM Bureau of Geology, James Callegary at USGS Arizona Water Science Center, Randy Hanson at USGS, Sharon Megdal, Robert G. Varady and Christopher Scott at University of Arizona, Matt Webb, Rima Petrossian, Robert Bradley and Bryan Anderson at Texas Water Development Board, and Domingo A. Silva Gamboa at CONAGUA for their generous help.

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