Groundwater

Issue Paper/

Aquifers Shared Between Mexico and the United States: Management Perspectives and Their Transboundary Nature

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Abstract

Totally 36 aquifers have been identified along the Mexico-U.S. border. Of these, only 16 have adequate data to provide a reasonable level of confidence to categorize them as transboundary. Limited and/or contrasting data over the other aquifers in the region reflects the void in transboundary groundwater management and assessment mechanisms throughout much of the Mexico-U.S. border. This paper identifies management mechanisms, structures, and institutional prioritization related to transboundary aquifers shared between Mexico and the United States. It also evaluates the differences in the transboundary nature of these aquifers, and how their combined hydrological and geographical considerations interrelate with local and regional social, economic, political, and even scale dimensions to create complex management challenges.

Introduction

Characterizing and identifying transboundary aquifers along the Mexico-U.S. border constitutes a major research challenge considering the limited and contrasting available data, as well as the discrepancies in methods used by the corresponding state and federal agencies within the various jurisdictions along the border. Recently, 36 aquifers were identified along the Mexico-U.S. border (Sanchez et al. 2016). However, the available data confirmed with a reasonable confidence level that only 16 of these aquifers are demonstrably transboundary; the evidence for the transboundary nature of the other 20 aquifers is only moderate to limited (Sanchez et al. 2016).

The challenge for identifying the transboundary nature of aquifers on the Mexico-U.S. border is further complicated by the absence of any management and governance mechanisms for transboundary aquifers. The only official effort to seek binational groundwater management appears in the form of Minute 242, an amendment to the 1944 *Treaty Between the United States of America and Mexico Relating to the Utilization of the Waters of the Colorado and Tijuana Rivers and of the Rio Grande* (1944 Treaty), which limits extractions on the transboundary Yuma Aquifer between the states of Arizona in the United States and Sonora in Mexico. Otherwise, there has been no effort on either sides of the border to address the groundwater management from a binational perspective.

This scenario, however, is not unique to the Mexico-U.S. border. Globally, while nearly 600 transboundary aquifers and aquifer bodies have been identified, only four have formal, binational, or multinational mechanisms for cooperation: the Genevese Aquifer, managed collaboratively between France and Switzerland; the Al-Sag/Al-Disi Aquifer between Jordan and Saudi Arabia, which implemented extraction and pollution controls; and the Nubian Sandstone Aquifer and Northwestern Sahara

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Aquifer, both in northern Africa and both of which employed data sharing regimes (IGRAC 2014; Sanchez et al. 2016).

Separately, a number of local border communities have developed locally specific transboundary water management strategies to cope with local water needs (Eckstein 2013). These efforts have tended to focus on surface water issues and rarely on groundwater management considerations. Nonetheless, these unofficial arrangements have opened the door for discussions over the scope and scale of transboundary groundwater assessments beyond the traditional basin approach (Sadoff et al. 2008; Varis and Tortajada 2008; Aguilar and Iza 2011; Giordano et al. 2016).

The confidence level of transboundary aquifers in the region identified by Sanchez et al. 2016, is based on available hydrogeological data that confirms at three different degrees of confidence the transboundary linkages of an aquifer. *Reasonable* confidence level refers to aquifers for which there is convincing hydrogeological and related evidence of transboundary hydrological linkages. The second category (*Some* confidence level) describes aquifers with some measure of evidence of hydrogeological transboundary linkages, but where the data are inconclusive. The final category (*Limited* level of confidence) refers to aquifers known to be located on the border, but where the available hydrogeological and other data are inadequate to suggest transboundary linkages.

While hydrological conditions are critical for determining the transboundary character of border aquifers, the transboundary nature of these aquifers should also be evaluated in terms of social, economic, political and institutional dimensions, at the local as well as regional levels (Sadoff et al. 2008; Venot et al. 2011; Söderbaum 2015). As will be discussed in this paper, such an approach could offer new elements for assessing transboundary governance schemes and developing more efficient transboundary management strategies.

The purpose of this paper is to identify existing groundwater management mechanisms for border aquifers shared between Mexico and the United States. The paper also addresses differences between the transboundary nature of aquifers and the important roles that such differences play in defining the binational and local agendas beyond hydrological conditions. The analysis is based and builds on the efforts of Sanchez et al. 2016, to identify and characterize transboundary aquifers along the Mexico-U.S. border (see Figure 1).

It is important to mention that considering the limited literature, both on physical conditions and managerial options for most of the transboundary aquifers located in the border region, this paper does not offer an in depth analysis of the challenges facing the transboundary management of these aquifers. Rather, it reviews the actual management regimes currently in place without attempting to identify the management possibilities that could result in conflict or even solutions for mismatches in management. Considering the lack of adequate data as well as the existing management conditions in the region, such an attempt would result in excessive speculation and weaken the paper's assumptions. Accordingly, the discussion of management regimes is limited to a summary of the most important elements that could play a role in any transboundary management attempt along the border.

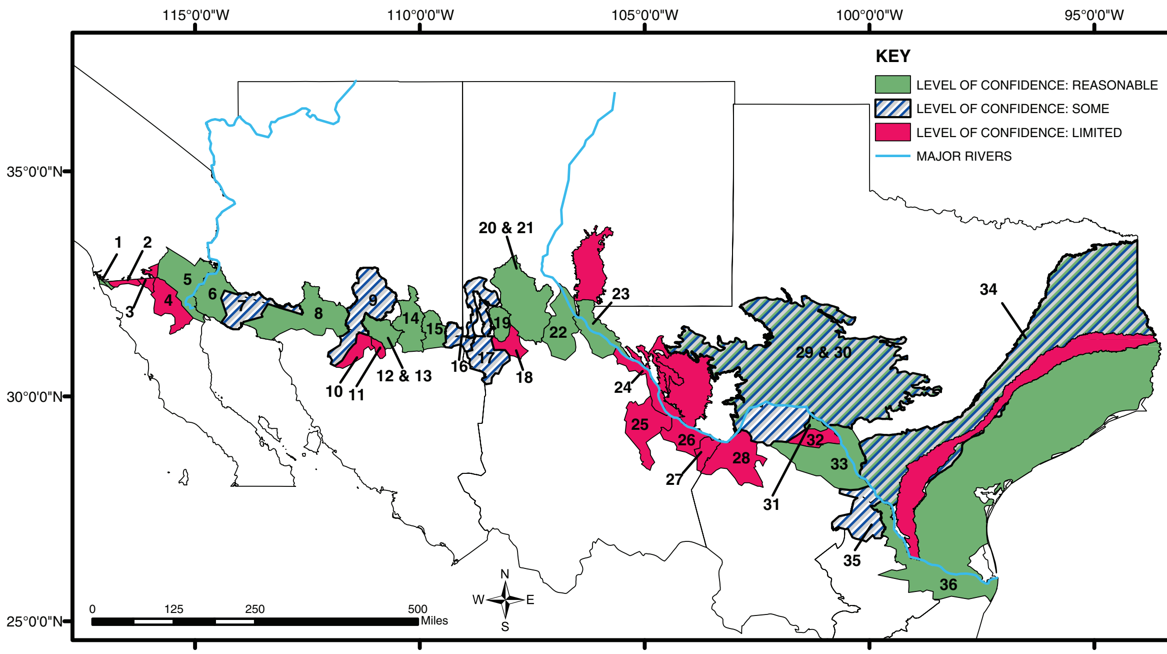
The Overall Binational Management Picture

In Mexico, all groundwater resources are managed by the federal water agency Comisión Nacional del Agua (CONAGUA or National Water Commission). The Mexican government divides the country into Hydrological Basins, which are administratively delineated regions as a means for decentralizing surface water management. Each Hydrological Basin has a Basin Council that is responsible for representing stakeholders water needs, coordinating the implementation of CONAGUA's regulations, and facilitating the planning and communication process between national and local stakeholders to improve water management at a regional scale.

Aquifer boundaries, however, are determined separately from those of Hydrological Basins and may or may not coincide with the administrative boundaries of Basin Councils. Therefore, the planning process is challenged by both hydrological and administrative boundaries that make groundwater management at national, state, and local levels, as well as in the international dimension, very difficult. For some aquifers, CONAGUA has established a Comité Técnico de Aguas Subterraneas (COTAS or Groundwater Technical Committees) to serve as liaisons between CONAGUA, the Basin Councils, and groundwater users. The purpose of COTAS is to encourage users to comply with existing regulations and to promote groundwater conservation. However, there are no enforcement mechanisms in place, and funding for compliance incentives is limited (CONAGUA 2011). Moreover, if a COTAS is not created for a specific aquifer, Basin Councils focuses their efforts primarily on surface water regardless of the presence of underlying aquifers.

In contrast, each state in the United States has jurisdiction over surface and groundwater resources within its respective territory. Aquifer boundaries are delimited and assessed under each state's individual basin priorities and by geographical boundaries. For example, while the Tijuana-San Diego transboundary aquifer system (Aquifer 1, see Figure 1) is hydrologically connected to the Tijuana River downstream of the river's drainage area on the U.S. side, it might seem logical to approach the region as a whole aquifer-river system for potential management purposes. Nevertheless, while California regulates surface waters at the State level, it allows local authorities to regulate and manage aquifer basins locally, either through water agencies, groundwater ordinances, or court adjudications (DWR 2003).

As a result, it is very common for individual transboundary aquifers in the four U.S. states bordering Mexico to be subject to multiple management and regulatory regimes. For example, the counties of San Diego and



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

Figure 1. Confidence level of the transboundary nature of aquifers/basins between Mexico and the United States (Sanchez et al. 2016).

Imperial both overlie different sections of the Tijuana-San Diego transboundary aquifer system on the U.S. side of the boundary and manage the groundwater independently of each other through local groundwater ordinances. The same aquifer on the Mexican side is administratively part of Hydrological Region I, which covers the complete territory of two states (Baja California Norte and Baja California Sur), and is under the jurisdiction of its corresponding Basin Council. For various reasons that require additional analysis, the institutions on the two sides of the border operate independently and rarely if ever communicate or coordinate their efforts. Consequently, while local approaches might not necessarily be inadequate for transboundary aquifer management (Giordano et al. 2016), the fact that they typically operate independently without considering a holistic approach and an aquifer-wide objective, limits the efficiency of management at a scale of the aquifer itself.

At the binational level, the International Boundary and Water Commission (IBWC), which administers surface water resources between Mexico and the United States according to the 1944 Treaty, does not have explicit authority to manage groundwater traversing the boundary between the two countries. Its jurisdiction in relation to groundwater is unclear, undefined, and has yet to be tested. However, it is the agency that executes interpretations and amendments to the 1944 Treaty (known as "Minutes"), including Minute 242 of 1973, which limited groundwater extraction in the Yuma Aquifer (Mumme 2003). This circumstance suggests that the opportunity to develop more extensive authority over transboundary groundwater may, to some extent, already exist.

Groundwater Management Along California's Border with Mexico

The California Statewide Groundwater Elevation Monitoring Program (CASGEM) prioritizes and ranks the state's groundwater basins according to their reliance on groundwater as low, medium, or high based on: overlying population; projected population growth; number of public supply wells; total number of wells; overlying irrigated acreage; reliance on groundwater as the primary source of water; impacts from overdraft and land subsidence, as well as saline intrusion and other forms of water quality degradation; and other relevant information (DWR 2014b). At the same time, the California Department of Water Resources (CA-DWR) has categorized groundwater basins according to Groundwater Budget Type in relation to the sufficiency of basin data for estimating water balances: A-type basins have the most data while C-type basins have the least. The Tijuana-San Diego aquifer basin within California (Aquifer 1), as well as adjacent basins, have been categorized by CASGEM as very low priority groundwater basins for management purposes (DWR 2014a). Similarly, of the four groundwater basins in California's portion of the Tijuana-San Diego transboundary aquifer system, CA-DWR has designated only the Tijuana basin as an A category basin and classified the others as C-type basins (DWR 2003). As a result, funding and management prioritization of transboundary aquifers in this region is limited.

Furthermore, the Jacumba Valley, Potrero Valley, Campo Valley, and Davis Valley aquifer basins within the United States are comparatively small in size and have been assigned by CASGEM as low-priority level basins (DWR 2014a). While the Jacumba Valley aquifer has been classified as an A groundwater budget type, there is little data about these aquifer basins pertaining to their transboundary character.

In the case of Valle de Mexicali Aquifer/Imperial Valley, Ogilby Valley, and Yuma Valley Aquifer (Aquifer 5), and the Valle de San Luis Rio Colorado Aquifer/Yuma Aquifer (Aquifer 6), two states in the United States (California and Arizona) with different management approaches and two states in Mexico (Baja California and Sonora), with a federal centralized management approach, have authority to manage these groundwater resources. Aquifer 6, is the only aquifer subject to a limited management regime—under Minute 242—between Mexico and the United States (IBWC 1973). Even though there is no deficit reported in this aquifer in Mexico (Sanchez et al. 2016), water quality and extractions are permanently monitored by the IBWC on both sides of the border according to the provisions of Minute 242.

Groundwater Management Along Arizona's Border with Mexico

Arizona identifies its groundwater priority regions as Active Management Areas (AMA) where groundwater pumping is restricted locally in relation to safe-yield criteria. The state also classifies certain regions as Irrigation Non-expansion Areas (INAs) in which the amount of irrigable land is limited to prevent over-pumping underlying groundwater (ADWR 2013). Examples of such AMAs include the Santa Cruz Aquifer AMA (Nogales/Santa Cruz Aquifer [Aquifer 12], and Rio Santa Cruz/Santa Cruz-San Rafael Aquifer [Aquifer 13]), where agriculture is highly dependent on groundwater resources; and the Douglas INA (Agua Prieta/Douglas Aquifer [Aquifer 15]), which is one of the two Arizona INAs in which the state has restricted the growth of irrigable land as a result of declining groundwater levels. An exception to state involvement in Arizona pertains to the Los Vidrios-Mexican Drainage Aquifer where 60% of the land overlaying the aquifer is federally owned and managed by the U.S. Fish and Wildlife Service as the Cabeza Prieta National Wildlife Refuge (ADWR 2009). As a result, State intervention in this aquifer is limited.

In Arizona, groundwater resources along the Mexican border have undergone extensive research and data collection as a result of the nearly 50-year old Arizona-Sonora Commission, a unique transboundary organization that has no parallel elsewhere on the border. In the case of Aquifers 12 and 13, and the San Pedro/San Pedro Aquifer (Aquifer 14), these groundwater bodies have been recognized as transboundary aquifers under the International Shared Aquifer Resources Management (ISARM) initiative, a multi-agency effort led by the United Nations Educational, Scientific and Cultural Organization (UNESCO) and the International Association of Hydrogeologists (IAH), as well as by Mexico, and selected as priority aquifers for further research under the Transboundary Aquifer Assessment Program (TAAP) initiated in 2006 by the United States (Megdal and Scott 2011). In fact, the two sections of the IBWC, along with other partners in both countries, just released a final report on Aquifer 14 (Callegary et al. 2016).

The TAAP is a U.S. federally funded research program designed to generate data and information on priority aquifers along the U.S. border with Mexico in Arizona, New Mexico, and Texas. Under the TAAP, criteria used to identify priority aquifers for research and funding allocation included: proximity to areas of high population density, extent of aquifer utilization, and susceptibility of transboundary aquifer contamination (Callegary et al. 2013). This is why, for example, extensive data and information have been generated for Aquifer 14. In comparison, the Sonoyta-Papagos/Simon Wash transboundary aquifer system (Aquifer 8), which has been recognized as a transboundary aquifer by both governments (Sanchez et al. 2016), has not received the same research attention. That aquifer does not underlie a highly populated area on either side of the border and water demand is not significant. Moreover, because 90% of the area in Arizona overlying the aquifer is located within the Tohono O'odam Indian Reservation, state groundwater management efforts in that region are limited (tribes in Arizona are not required to register wells with the Arizona Department of Water Resources).

It is worth mentioning, that for many of the aquifers traversing the border between California and Baja California and Arizona and Sonora, in particular, aquifers 1, 5, 6, 8, 12, 13, and 14 (see Figure 1), there seems to be a relationship between the recognition of the transboundary character of those aquifers (by Mexico, the United States, Arizona and California, as well as under ISARM) and associated surface water quality challenges impacted by groundwater-surface water linkages representing a public health risk in highly populated border communities (Blanco et al. 2001; Sanchez et al. 2016). In other words, the more that health risks are associated with poor water quality (either surface or groundwater), the greater the interest that is given to transboundary linkages. Notwithstanding, recognition of this risk has not necessarily implied the recognition of the need to approach groundwater management from a holistic transboundary approach. With the exception of the Yuma Aquifer, no other transboundary aquifer on the Mexico-U.S. border has been subjected to any management plans or pumping restrictions at the binational level. Although groundwater pumping restrictions do not necessarily guarantee aquifer sustainability, they do reflect a tendency toward what was recently referred to as a "low-regret step that allows for adaptive management objectives" (Jarvis 2014).

Groundwater Management Along New Mexico's Border with Mexico

In New Mexico, groundwater and surface water management are conjunctively administered by the State Engineer. As a result, conservation programs integrate strategies for interrelated surface and groundwater resources. For groundwater basins, the state has developed two categories of water restrictions based on the level of water stress experienced in the basin: Mined Groundwater Basin where the state restricts the issuance of new water permits for an indefinite period of time; and Critical Management Areas (CMA), which are areas located within a mined basin that require more specific and stricter water use restriction.

The Conejos Medanos/Mesilla Bolson (Aquifer 22) in New Mexico is designated a CMA for which the state has imposed pumping restrictions and developed strict conservation programs (Darcy 2012). However, the long-term efficiency of these restrictions has yet to be evaluated. In addition, due to agricultural activities and the high density of septic systems, groundwater contamination is a major concern in the New Mexico portion of this aquifer (TWDB and NMWRRI 1997). On the Mexican side of the aquifer, there are no pumping restrictions. Development of the aquifer is still somewhat limited, although for the last 6 years the aquifer has provided drinking water to the city of Ciudad Juarez through a 40-km aqueduct as a complementary source of freshwater for the city, given the overexploitation and deteriorating quality of the Hueco-Bolson Aquifer (Aquifer 23).

New Mexico is the only border state in the United States that has delineated aquifer boundaries irrespective of the geographical boundaries. Nevertheless, apart from Aquifer 22, Josefa Ortiz de Dominguez Aquifer (Aquifer 20), and Las Palmas/Mimbres Aquifer (Aquifer 21), all of which have been recognized as transboundary by both governments according to the ISARM inventory and have been assessed within New Mexico to varying degrees (particularly Aquifer 22), the rest of the aquifers in this region have not received priority in terms of research or groundwater management assessments.

Groundwater Management Along Texas's Border with Mexico

Texas delegates authority to regulate groundwater extraction and uses to local Groundwater Conservations Districts (GCDs) where such GCDs have been created. Approximately 85% of the state's land area is subject to one of the 99 GCD in Texas (TWDB 2017). The state also assigns Regional Water Planning Groups the responsibility to make recommendations to the Texas Water Development Board (TWBD) regarding groundwater management within their corresponding geographic management units. The TWDB categorizes the state's aquifers as major and minor aquifers depending on the amount of water supplied. The Texas share of the Conejos-Medanos/Mesilla Bolson (Aquifer 22) and Valle de Juarez/Hueco Bolson (Aquifer 23) are not subject to any GCD. Nevertheless, they both fall under the jurisdiction of the Far West Regional Water Planning Group (E), which has recommended the conjunctive use of groundwater with surface water from the Rio Grande as well as investment in water desalinization (TWDB 2007). Legally, the principle of "rule of capture," often described as the law of the biggest pump, stills governs groundwater use in the State. While many GCDs have implemented pumping limitations on individual wells, only the Edwards Aquifer Authority (EAA) and the Harris and Fort Bend Subsidence Districts have implemented abstraction restrictions over a broad geographic area. Other GCD's that have attempted to impose an overall cap on the total amount of groundwater that can be extracted from a particular aquifer have faced political challenges and even law suits and have had a difficult time enforcing these restrictions (Chavez 2000; George et al. 2011; Hathaway 2011; Kaiser 2016).

In terms of groundwater shared between Texas and Mexico, in addition to Aquifers 22 and 23, there are four aquifers worth highlighting: the Edwards-Trinity-El Burro aquifer (Aquifer 29), Allende/Piedras Negras-Local Aquifer (Aquifer 33), Hidalgo/Carrizo Wilcox Aquifer (Aquifer 34), and Gulf Coast Aquifer (Aquifer 36). Aquifer 29 is particularly significant because it underlays the City of San Antonio, with its 1.4 million inhabitants who are primarily dependent on groundwater for municipal use, and portions of the aquifer are subject to the authority of the EAA. Within Texas, however, various geographic sections of Aquifer 29 are also managed and regulated by other groundwater authorities: the Headwaters GCD in Kerr County and the Real-Edwards Conservation and Reclamation District govern groundwater management over their respective portions of the Edwards-Trinity Plateau; the Kinney County GCD regulates groundwater extraction and use on the Edwards Fault Zone; and the Bandera County GCD manages groundwater in the Trinity Aquifer. The Regional Planning Group of the Edwards-Trinity Plateau (Plateau Water Planning Region J) has recommended to the TWDB to develop strategies to construct a well field in Kerr Country and public supply wells in Real County (George et al. 2011). More recently, the Regional Planning Group prioritized water conservation strategies, including water reuse, as traditional sources of water have become more scarce (Ashworth et al. 2016).

Aquifer 33 has no established GCD in Texas. While the Rio Grande Regional Planning Group M encompasses this aquifer area, that group is mainly focused on the Carrizo Wilcox, Yegua, and Gulf aquifers (George et al. 2011). For the corresponding Texas share of Aquifer 34, which contains mainly brackish groundwater, Region M integrates 27 Irrigation Districts to manage surface water from the Lower Rio Grande and the Starr GCD, whereas Webb, Hidalgo, Zapata, and Cameroon Counties do not have a GCD established. To meet the water needs of the region's growing population—projected to reach 4 million by 2070—Regional Planning Group M has recommended focusing on desalinization of brackish groundwater, surface and groundwater conjunctive use strategies, water reuse (particularly direct reuse), and the transport of surface and groundwater over long distances (George et al. 2011; TWDB 2015).

Excessive pumping of Aquifer 36, as well as problems with subsidence, led to the creation in 1975 of the Harris-Galveston Subsidence District whose purpose is to regulate groundwater extraction to prevent subsidence and flooding (HGSD 2013). Fifteen years later, the neighboring Fort Bend Subsidence District (which also underlays Aquifer 36) was created with the same objective (FBSD 2013). Today, there are also five regional planning groups that have jurisdiction over different portions of the Aquifer 36 (Regions K, L, N, M, and H). Recommendations from these various bodies to address depletion and subsidence range from expansion of water treatment facilities, large-scale conveyance projects, desalination of brackish groundwater, developing conjunctive use projects to create new sources of freshwater, and reducing dependency on groundwater, among others (George et al. 2011; TWDB 2016).

One other factor worth noting is that Texas utilizes geological boundaries to delineate aquifer limits, whereas Mexico and the rest of the states in the United States use either a true (saturated zone) or basin boundary (catchment area) methodology, or a combination of both. Therefore, the attempt to reveal the transboundary aquifer puzzle is even more challenging on Texas's border with Mexico (Sanchez et al. 2016).

Groundwater Management Along Mexico's Border with the United States

Under Mexican federal regulations, pumping restrictions are divided into three categories: Veda Type III restrictions, which are considered to be "ordinary" pumping restrictions where new groundwater rights are limited for urban, industrial, irrigation, and other uses; Veda Type II restrictions, which restrict new water rights solely for domestic uses; and Veda Type I restrictions, which are the most stringent restrictions and recognize that any new water permits will jeopardize groundwater availability in the aquifer (CONAGUA 2012b). These regulations, which can only be issued and enforced by the Federal government, apply only to new extractions and serve as the basis under which CONAGUA manages applications for new groundwater permits. The regulations, however, do not specify how much groundwater can actually be extracted by new permit holders and do not address sustainable yield. In addition, Veda restrictions do not apply to preexisting extractions making monitoring of overall pumping more challenging. The Public Registry of Water Rights (REDPA) is the operational branch of CONAGUA that registers groundwater extractions by users. However, there is no enforcement mechanism to ensure that users register their water use. Moreover, there is no trustworthy oversight system that monitors the amount of water being extracted (Sanchez-Flores et al. 2010). This lack of enforcement is evident in various Mexican groundwater availability reports that show a mismatch between the actual amounts of groundwater extracted from specific aquifers, according to technical studies, and official amounts of water rights registered with REDPA (Sanchez-Flores et al. 2010).

All of the aquifers along the border between Mexico's Pacific Coast and the area of Ciudad Juarez—Aquifer 1 to Aquifer 23—have *Veda* restrictions. In Baja California, they are mostly Type III, while in Sonora and the northwestern part of Chihuahua, they are primarily Type II. A *Veda* Type I restriction has been applied to the irrigation district no. 14 in Sonora, located between Aquifers 5 and 6, primarily to comply with the restrictions imposed under Minute 242. As for aquifers located along the rest of Mexico's border with the United States—Aquifers 24 to 36—apart from one Type II *Veda* restriction applied to irrigation district no. 25 in Tamaulipas overlaying Aquifer 36 (Bajo Rio Bravo), the rest of the border aquifers in Chihuahua, Coahuila, Nuevo Leon, and Tamaulipas do not have any *Veda* restrictions (CONAGUA 2012b).

A principal concern relating to groundwater management along the Mexico-U.S. border pertains to the 1998 establishment of COTAS, which were intended to engage the community of groundwater users to comply with CONAGUA regulations, promote the registration of water rights with REDPA, and support the initiatives of Basin Councils (CONAGUA 2011). Despite the well-meaning intentions, these entities have been assigned practically no enforcement authority. Moreover, only two aquifers in the entire border region—the Janos/Animas and Playas Aquifer (Aquifer 17) and Ascencion/Hachita Moscos Aquifer (Aquifer 18)—have been made subject to a COTAS due to scarce funding (CONAGUA 2012a). In addition, the implications of the COTAS mechanisms have never been established in terms of groundwater conditions before and after installation of a COTAS, or in terms of gauging compliance of groundwater users (Sanchez-Flores et al. 2010; CONAGUA 2011).

Another concern, related to the severe drought that endured from 2011 to 2012, is the federal government's 2013 suspension of *libre alumbramiento* (free extraction allowance) in the most water-scarce regions of the country (primarily in the northern states). The *libre alumbramiento* was designed to attract unregistered groundwater users to come into compliance with CONAGUA regulations (*Veda* restrictions) and prevent over-exploitation of aquifers. With the exception of Aquifers 17, 18, 19, and 33, all border aquifers in Chihuahua, Coahuila, and Nuevo

Leon, along with Aquifer 13 in Sonora, continue to be subject to the suspension, while the remaining border aquifers in Sonora, Baja California, and Tamaulipas are not (CONAGUA 2014).

The Transboundary Nature of Aquifers

As has been mentioned, available data suggest that there may be 36 aquifers traversing the border between Mexico and the United States. Although it is highly unlikely that an aquifer could end abruptly at a political borderline, not every aquifer that physically crosses the Mexico-U.S. border has been recognized as transboundary per se. In fact, the official use of the term "transboundary aquifer" at the binational and even international level is charged with political and legal content and is carefully used during binational conversations. This suggests that a more nuanced approach of transboundary aquifer may be warranted, one that recognizes the reality that the transboundary nature of an aquifer is more a function of the attention that aquifer riparians give to a particular border aquifer rather than a simple geographic or hydrologic exercise. Such an approach may be referred to as the "transboundariness" of an aquifer and would encompass the extent to which aquifer riparians prioritize a particular aquifer over another and recognize its value in the context of economic, environmental, social, cultural, and legal-institutional criteria. This approach recognizes that each aquifer is singular and is dependent on its local context; it encompasses human and physical components through which the transboundary nature of an aquifer may be best valued, measured, and compared. In other words, it is not simply the physical aspects of an aquifer that makes it a transboundary resource (although an underlying physical transboundary condition is required). Rather, it also is the surrounding circumstances of the transboundary elements related to the aquifer (e.g., political, social, economic, institutional, historical, cultural, legal, etc.) that drive and extend its limits in different dimensions and at different scales (Venot et al. 2011; Giordano et al. 2016). The simple fact that an aquifer is recognized as transboundary by its sharing countries provides a particular political dimension, at both local and binational levels, in contrast to those that have not been recognized as such. The management prioritization and categorization process is, therefore, a function of each aquifer's multidimensional transboundariness.

This type of prioritization and recognition is quite common and evident around the world, including with the transboundary aquifers inventoried by ISARM. That compilation is based on submissions made by individual nations throughout the Americas, rather than the collection and processing of original data (TWAP 2012), and information and designations provided by the countries do not always coincide with hydrological or scientific data of transboundary aquifers found in other sources. In fact, one of the main objectives of ISARM's international efforts is to identify which transboundary aquifers are recognized by which nation according to each nations' sovereign criteria (TWAP 2012; ISARM 2015). Accordingly, the transboundariness of an aquifer can also be the product of a process that continues to evolve as political, social, economic, environmental, institutional, and international conditions change, particularly at the local level.

For example, even though Aquifer 6 and Aquifer 23 are both transboundary aquifers, in terms of hydrogeology and geography, facing similar challenges, their transboundary nature is contextualized in terms of different institutional-legal, political, economic, and even cultural-historical relationships that makes each aquifer unique. Aquifer 6 (Yuma Aquifer) is subject to the only binational arrangement between Mexico and the United States, which came as a result of intense political pressure driven by agricultural loses on both sides of the border and high salinity levels in the Colorado river. This scenario has not been replicated in the highly populated region of Aquifer 23 (close to 2 million inhabitants compared to approximately 300,000 in the Yuma aquifer area) where over pumping and water quality concerns have yet to achieve a high enough risk that would spur both countries to implement a cooperative arrangement to restrict abstractions, jointly manage the aquifer, or achieve some other response. In contrast, security concerns related to smuggling and unresolved crimes in Ciudad Juarez have been paramount and have overshadowed groundwater issues in the region's political agenda.

Likewise, although there is reasonable data to confirm the transboundary nature of aquifers 15, 19, and 33 (Sanchez et al. 2016), the three cases have complete different stories, scenarios, institutional engagements, and magnitude of hydrological challenges. Aquifer 33 is not recognized officially as transboundary by the state of Texas, even though data from the Mexican side and joint technical studies have verified its transboundary linkages. Therefore, the transboundary nature in this aquifer is limited by institutional and political perspectives. In comparison, Aquifers 15 and 19 have gained international recognition under ISARM's inventory, and thereby preference for future assessments.

Aquifers 15, 17, and 18 (Ascencion/Hachita Moscos) provide yet another example of the differences in transboundariness. Aquifers 17 and 18, located on the border between Chihuahua and New Mexico where population density is low and associated groundwater contamination risks have not reached the level of a health threat, have a transboundary nature that is limited primarily to their physical transboundary character. In contrast, nearby Aquifer 15, which underlies a region of high population density and where water quality health risks related to wastewater discharges in the shared Agua Prieta River led to the implementation of local agreements to improve water quality, has important social and political elements that must be considered in addition to the physical and hydrological conditions of the aquifer.

The transboundary nature of an aquifer is not a static condition; it varies depending on the elements and dimensions involved and can also be measured and valued in economic terms (Agstner 2016). When neighboring countries recognize an aquifer as transboundary, it is usually because other critical factors beyond the hydrological have been identified or have expanded the physical boundaries to include water demand, contamination, population growth, economic value, and other concerns. Aquifers 7, 9, 16, and 17 (see Figure 1) have been identified as having reasonable data to categorize them as physically transboundary (Sanchez et al. 2016). Nonetheless, besides their relative hydrological boundaries, no other dimensions (such as social, institutional, or political) have been identified to further characterize and support their transboundariness. Still, these aquifers have their own hydrological, geographical, social, and institutional dimensions that are different among them and can always change over time and/or space.

In addition, the transboundariness of an aquifer can increase (as higher risk factors are introduced), or stabilize over time when sustainable approaches are applied. For example, Aquifer 22 has been categorized as transboundary in terms of hydrogeology and geography. That aquifer's transboundariness, however, is not homogeneous throughout its extent. The Mexican side of the aquifer has different social and water demand conditions than on the U.S. side of the aquifer where higher challenges have been identified due to intense overpumping. As a result, it is fair to say that the aquifer's transboundariness is lower on the Mexican side than that on the U.S. side. This condition, however, is likely to change as artificial recharge projects are explored and water transfers to Ciudad Juarez are implemented in the Mexico side (SGM 2010; Sanchez et al. 2016).

Similarly, the Valle del Peso/Texas Bolsons (Aquifer 24), for which the available data resulted in a determination of limited confidence on its transboundary nature (Sanchez et al. 2016), has been considered a potential storage aquifer to supply water to the City of El Paso (George et al. 2011). As the aquifer becomes more relevant as a new source of fresh water for the region, and as more information is generated about its character, the aquifer's transboundary nature could increase as it become more strategic to the region's water supply and depending on whether the new information support its physical transboundary character.

Proposed Criteria to Measure the Level of Aquifer "Transboundariness"

It is worth mentioning that the transboundariness of an aquifer should not be understood as the level of importance of that aquifer. The relative importance of an aquifer relies on the aquifer conditions and variables that define them (hydrological, environmental, social, economic, cultural, and political). In contrast, the transboundariness of an aquifer measures and evaluates the same variables but at a binational/international level, adding the transboundary element into the analysis that redefines the nature of the aquifer, its boundaries, extents, conditions, dimensions, scales, and value as a geostrategic resource. It is a measure of the implications of having and identifying an aquifer that happen to be shared by two or more countries.

The proposed criteria to measure the level of transboundariness of an aquifer are described below. However, as this paper offers the first introduction to this approach, it will not attempt to quantitatively measure or analyze its applicability in any specific aquifer. The primary objectives here are to offer a clear understanding of the elements and variables that are being considered under this new perspective, and to lay a foundation upon which to implement this approach in a subsequent analysis.

The criteria used in this approach encompass political, social and institutional, as well as physical parameters to evaluate the different dimensions upon which an aquifer relies. The first proposed criterion is population. As noted above, a highly populated urban center makes a difference in the attention and treatment of corresponding authorities on both sides of the border. A second criterion is groundwater dependency for any use, regardless of the economic activity or extent of reliance for industry, domestic, or agricultural purposes. As the extent of a particular dependency or its economic value increases, the greater the weight that should be given to this criteria in determining an aquifer's transboundariness. The third criterion is water quality/quantity challenges. This criterion considers both the condition of the aquifer as well as water quality issues (both surface and groundwater at local or regional level), and includes issues related to groundwater deficit (over-exploitation) and contamination (surface or groundwater).

These three proposed criteria are based on previous aquifer classifications that included similar variables to evaluate vulnerability and physical conditions of aquifers for management purposes (Berardinucci and Ronneseth 2002; Moro Ingenieria 2006). Four additional criteria are proposed here in order to describe the transboundariness of an aquifer. The fourth criteria comprises the availability of data and research on the aquifer; the fifth considers political recognition of the transboundary nature of the aquifer by some or all of the riparians, as well as by international institutions; the sixth encompasses the existence of water-related cooperation efforts at binational, regional, or local levels; the seventh focuses on other issues governing the local agenda (water and non-water related) that exert pressure on the binational relationship at the binational, regional, or local scale). While the fourth criterion is based on the classification of Sanchez et al. 2016, the last three criteria are intended to measure the political/institutional dimension of the transboundary nature of an aquifer based on recent transboundary cooperation classification studies (Conti 2014).

The goal and expectations of measuring the level of an aquifer's transboundariness will help in better understanding how and why nations prioritize their transboundary aquifers. As suggested above, future research will seek to better delineate the boundaries, parameters, and methodology of this approach, as well as seek to apply it to specific transboundary aquifers.

A Recall to the Local Approach

The differences among the transboundary nature of aquifers expose and emphasize the challenges facing efforts to develop homogeneous governing principles for transboundary aquifers (Jarvis 2014). The complexity—in variables, contexts, and dimensions—reinforces the thesis favoring more localized management strategies focused on small-scale applicability and ad-hoc principles, rather than basin-scale practices and approaches (Sadoff et al. 2008; Giordano et al. 2016). There are several examples of local agreements between border cities that have resulted in successful water management strategies regardless of the umbrella of the binational agenda. The water treatment plants in the cities of Nogales, Douglas, and San Diego on the U.S. side, which assure water quality in the transboundary river basins shared with the sister cities of Nogales, Agua Prieta and Tijuana on the Mexico side, respectively, are examples of ad hoc strategies that serve local, specific objectives and offer alternatives for management strategies (Graf et al. 2005). Although groundwater is not a primary focus of these efforts, they form a framework and pathway for cooperation and delimitation of locally specific, groundwater-related arrangements. In addition, it is not surprising that there are around 200 Minutes or Amendments to the 1944 Treaty, signed by Mexico and the United States, addressing site-specific water concerns, particularly local border sanitation issues, as well as water deliveries of the Colorado River and boundary delineation issues (IBWC/CILA 2017).

It is also noteworthy that the Genevese aquifer, which has been recognized the only transboundary aquifer that has been managed binationally (France and Switzerland), has indeed its own local dimension that played an important role in the success of its management regime. The original agreement signed in 1978 between the Canton of Geneva in Switzerland and the Prefecture of Haute-Savoie in France did not involve the federal governments of the two countries. Moreover, the fact that there were no transboundary cooperation agreements at the national level in 1978 provided space for the local communities and officials to negotiate an arrangement adapted to their own local needs, dimensions, and priorities. Lastly, the revised 2008 agreement again was signed by local and regional authorities, including local committees described as representatives of a "transboundary water community" (de los Cobos 2014), and was achieved recognizing the scale, dimension, and complexity of local contexts and management regimes that coexit above and beyond the binational agenda. The particularity of the local context and site-specific priorities and dimensions that took place under this agreement makes the likelihood of replicating the Genevese Agreement elsewhere an impossibility. Rather, what is needed is a broad, multidisciplinary approach based on the logic of contextual and local governance schemes, local hydrogeologies, and sociocultural patterns to improve the management of each particular transboundary aquifer (Agstner 2016; ISARM 2015). There is already evolving literature that recognizes the success of more local approaches vis-a-vis basin approaches, promoted by local institutions, in terms of transboundary aquifers management between Mexico and the United States (Eckstein 2013) as well as other parts of the world (Sadoff et al. 2008; Aguilar and Iza 2011; Venot et al. 2011; Söderbaum 2015; Holmatov et al. 2016).

Conclusions

Hydrological, geological, geographical, social, economic, political, and cultural conditions will continue to be key elements in identifying present and future transboundary challenges related to groundwater use and its importance for human and environmental well-being. The differences in mechanisms and approaches for the identification and characterization of groundwater resources that exist in Mexico and the border-states in the United States are not minor and reflect the magnitude of the challenges that must be addressed in the near future as water availability becomes scarcer. However, considering the differences in the transboundary nature of the aquifers found along the border, efforts related to the governance of transboundary aquifers should not focus on the development of homogeneous management practices. Rather, efforts must be made toward the differentiation of local management regimes that considers unique social, economic, political, cultural, and hydrological conditions and dimensions that, when considered together, make sense at a global-basin scale. In other words, the transboundariness of an aquifer and its corresponding management and governance schemes must reflect local needs from a global perspective.

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