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RESEARCH ARTICLE

The transboundariness approach and prioritization of transboundary aquifers between Mexico and Texas

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Abstract "Transboundariness" refers to a new approach that identifies and prioritizes transboundary aquifers using socio-economic and political criteria, improving their characterization by using other variables in addition to their mere physical boundaries. This approach is applied to the hydrogeological units/aquifers shared by Mexico and Texas, with the following results. First, the rankings agree with the current level of attention to transboundary aquifers in the region by both countries, providing a quantifiable system that could be tested in other transboundary aquifers. Second, this approach provides a holistic and integrative perspective for transboundary aquifer assessment and prioritization. Third, this prioritization exercise expands the criteria currently used into a more integrative regime of groundwater links to the community as a whole. Finally, the results reflect not only how the transboundary aquifers are being used (or neglected) but also the socio-political context of the populations that depend on these resources for current and future development.

Keywords Mexico · Prioritization · Texas · Transboundariness · Transboundary aquifers

INTRODUCTION

The most recent study on transboundary aquifers shared by Mexico and Texas finds that there might be up to 53 geological units following or crossing the border between the two countries (Sanchez et al. 2018). Of those 53 geological units, about half are estimated to have good aquifer potential based on lithological and hydrogeological characteristics, and good to regular water quality. Accordingly, half of the land in the border region also shares groundwater resources at different depths and scales. Considering the variables of urban population, economic development, cross-border social and cultural factors, and political considerations, the border region is a complex and diverse reality with multidimensional implications. Transboundary groundwater also has unusual and complex features: the resources themselves cannot be seen; the responsible jurisdictions do not necessarily follow the physical limits of the hydrologic structures; national and state procedures for the identification and study of the respective portions of the aquifers differ; exploitable areas of the resource underlie different governments; human–environment interactions are intricate, localized, and challenging; and border societies are often more socially, economically, and culturally connected to people close by but on the other side of the border than to other people in the same country.

Acknowledging and understanding the process of allocation of shared groundwater resources requires much more than science to assess, and much more than national policies to address. Communication, cooperation, negotiation, flexibility, adaptability, willingness, and trust are just a few of the key elements necessary to guarantee the development of productive science and the effective applicability of potential transboundary management policies.

Beyond its physical boundaries, an aquifer that extends across borders acquires social, economic, and political dimensions, which affect the attention and the importance given to it by users (or potential users) of the resource. *Transboundariness,* as proposed by Sanchez and Eckstein (2017), concerns the value of hydrological units/aquifers in their physical, social, environmental, and political contexts, and it attempts to measure the implications of those contexts for units/aquifers that span different political jurisdictions. According to this approach, the physical extent of an aquifer is not enough to make it transboundary. Other conditions—social, economic, environmental, and

political—have to be evaluated before the aquifer is considered a transboundary resource (Sanchez et al. 2016; Sanchez and Eckstein 2017). The importance of local conditions in the measure of the transboundariness of a given aquifer puts the scale and dimension of the boundaries of the aquifer in an alternative perspective. As explained by Sanchez and Eckstein (2017), transboundariness measures the environmental, social, political, economic, and hydrogeologic conditions of an aquifer at binational/international level, adding the transboundary element into the analysis, redefining its nature and *value as a geo-strategic resource*. "It is a measure of the *implications* of having and identifying an aquifer that happens to be shared by two or more countries" (Sanchez and Eckstein 2017).

As noted by previous research, transboundary groundwater management is basically nonexistent in the Mexico–United States border region (Sanchez et al. 2016; Sanchez and Eckstein 2017); the possibility of exploring possible models and new approaches to water management through the concept of transboundariness is the main driver of this ongoing research.

For this study, aquifer transboundariness is measured based on political aspects (political recognition, cooperation efforts), economic aspects (groundwater dependency for any use), social and institutional aspects (population, data availability), other issues governing the binational agenda (security, trade, immigration), and water quantity and quality challenges (surface and groundwater), in addition to physical parameters (Sanchez and Eckstein 2017). Figure 1 presents the transboundary hydrogeological units/aquifers identified in the Mexico–Texas border region.

Among the several aquifers in the border region, at present, only the Valle de Juarez/Hueco–Tularosa Bolson, the Conejos-Medanos/Mesilla Bolson, the Edwards Aquifer, and the Bajo Rio Bravo/Gulf Coast Aquifer have been recognized by the International Shared Aquifer Resources Management (ISARM) Initiative as transboundary aquifers shared by Mexico and Texas (Senate Reports 2006; International Groundwater Resources Assessment Centre IGRAC 2015). Of these, only the Valle de Juarez/Hueco–Tularosa Bolson and the Conejos-Medanos/Mesilla Bolson are considered priority aquifers at the binational level under the Transboundary Aquifer Assessment Program (TAAP) (Senate Reports 2006; Alley 2013; International Groundwater Resources Assessment Centre IGRAC 2015). Therefore, current research and binational attention has been concentrated on these two aquifers. The rest of the potential transboundary aquifers in the remaining 170 000 km^2 of shared land have been researched to a lesser extent. Additionally, the criteria used by TAAP (Senate Reports 2006) to prioritize these aquifers are limited to groundwater dependency, contamination vulnerability, and availability of other sources of water. The objective of this article is thus to measure the transboundariness of all the hydrogeological units/aquifers shared by Mexico and Texas identified by Sanchez et al. (2018), and apply the criteria proposed by Sanchez and Eckstein (2017): first, to identify hydrogeological units/aquifers that could be recognized eventually as transboundary; and second, to propose a methodology to prioritize units and regions for potential groundwater management based on their transboundariness.

The rest of the paper is organized as follows. It describes the methodology used, followed by the findings for the transboundariness of the hydrogeological units/aquifers shared by Mexico and Texas and their corresponding prioritization. The last part discusses the socio-economic and political situation in the border area, with details that support the proposed scores. It concludes with a reflection on the implications of this approach and its ability to reflect the reality of the transboundary nature of aquifers.

MATERIALS AND METHODS

The hydrogeological units/aquifers analysed in this study are those reported by Sanchez et al. (2018): (1) Conejos-Medanos/Mesilla Bolson, (2) Valle de Juarez/Hueco–Tularosa Bolson, (3) Red Light Draw Bolson, (4) Green River Valley Bolson, (5) Presidio Bolson, (6) Redford Bolson, (7) Cretaceous-Terlingua Aquifer, (8) Santa Fe del Pino Aquifer, (9) Serrania del Burro Aquifer, (10) Edwards Aquifer, (11) Eagle Ford Fm./Eagle Ford Group, (12) Presa La Amistad Aquifer, (13) Allende-Piedras Negras Aquifer, (14) Escondido Fm./Escondido Fm., (15) Carrizo-Wilcox Aquifer, (16) Bigford Fm./Bigford Fm., (17) El Pico Clay Formation/El Pico Clay Formation, (18) Palma Real-Guayabal Formation/Laredo Formation, (19) Yegua-Jackson Aquifer, (20) Catahoula Confining System, and (21) Gulf Coast Aquifer/BRB Aquifer.

These names indicate how they are recognized or identified, first on the Mexico side, then in Texas. The names that are repeated indicate hydrogeological units/aquifers with the same name on both sides of the border. In some cases, as the Bolsons, the name has been recognized only on the Texas side but because the boundaries extend into Mexico, the same name is used on the Mexico side. Likewise, in the cases of Serrania del Burro and Santa Fe del Pino Aquifers, the names correspond to the administrative aquifer boundaries identified in Mexico that extend to Texas.

In this study, the hydrogeological units/aquifers were prioritized based on their transboundariness as defined by Sanchez and Eckstein (2017). We also considered the criteria established by TAAP (Senate Reports 2006), as well

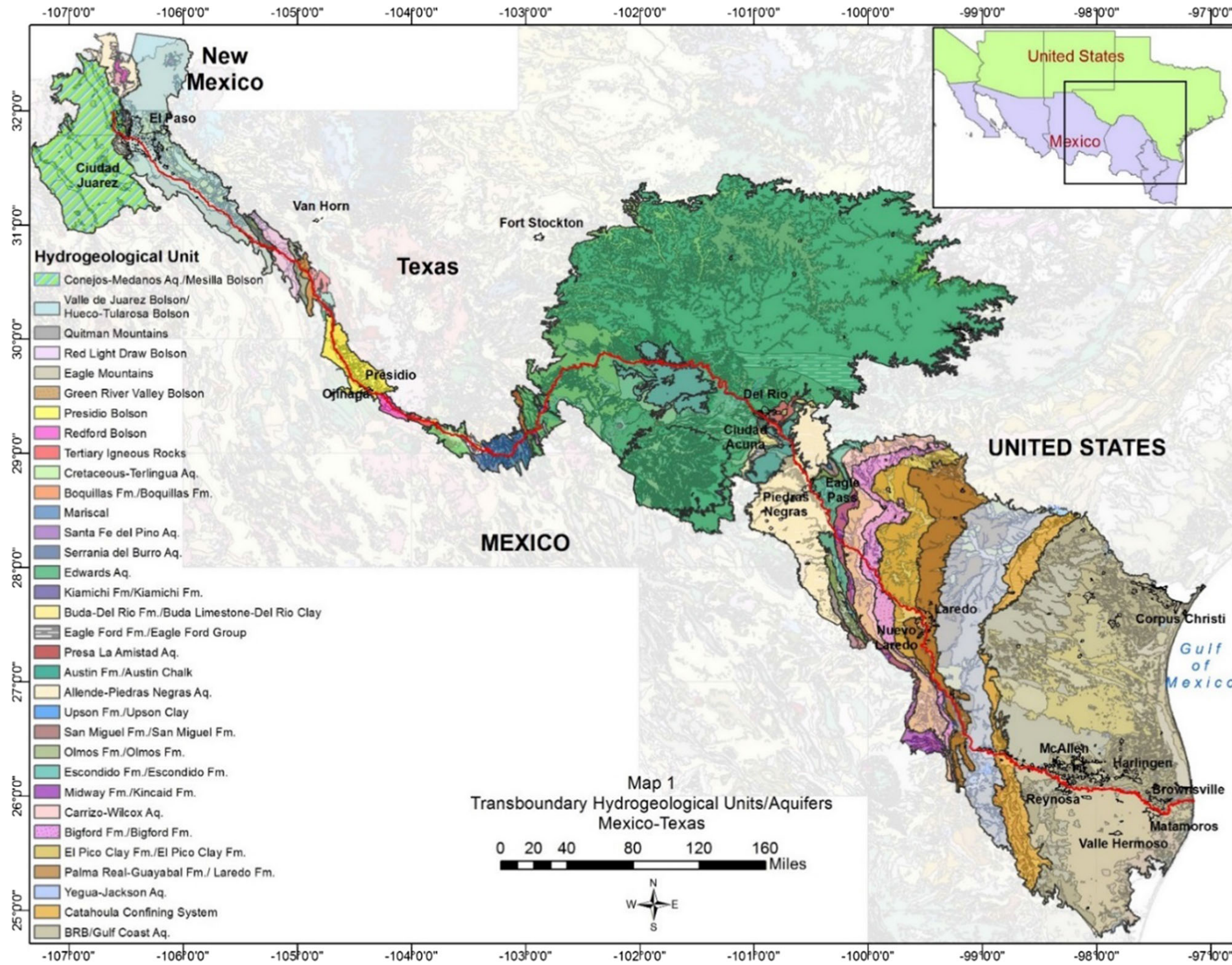

Fig. 1 Transboundary hydrogeological units/aquifers shared by Mexico and Texas. Adapted from Sanchez et al. (2018)

Table 1 Criteria to measure the transboundariness of hydrogeological units/aquifers

Population	Groundwater dependency (for any use)	Water quantity/quality challenges	Data/research availability	Political recognition (as transboundary)	Cooperation efforts	Other issues governing the agenda
3: > 400 000	3: > 70%	3: Deficit; salinity; contamination vulnerability	3: Reasonable	3: Both countries	3: Binational and local	3: Highly visible
2: 100 000–400 000	2: 40–60%	2: Deficit; signs of contamination starting to appear	2: Some: only on one side	2: Partial (one country or part of another system)	2: Some (local)	2: Some (partial; in one country)
1: < 100 000	1: < 30%	1: Not yet reported	1: Limited	1: None	1: Limited/ none	1: Limited

as the variables recommended by ISARM (International Groundwater Resources Assessment Centre IGRAC 2015): population (the sole social variable); groundwater dependency (for domestic, industry, agriculture or any particular use); water quality issues and conditions (groundwater and surface); status of binational recognition; local and binational management efforts; data availability as well as research on the aquifer (parts of the aquifer or the whole system); and any other issues governing the binational agenda (and not necessarily related to water), of which the most important are international trade, security, drug traffic, and immigration.

Based on all these criteria, the hydrological units/aquifers were given a score of 1, 2, or 3, where 3 is the highest and 1 is the lowest (Table 1). The scoring was then used to prioritize the groups. For the purpose of this study, "priority" refers to the level of attention and importance given to some hydrogeological units/aquifers over others as a result of their transboundariness.

Scope and limitations of the transboundariness approach

The transboundariness approach proposes a truly holistic perspective for analysing and addressing the nature of transboundary aquifers. However, the attempt to measure it and to develop a metric to prioritize some aquifers over others certainly has its own limitations and restrictions. The complexity of natural systems, specifically groundwater, which is linked to a variety of socio-economic and political aspects, challenges any attempt to quantify its uniqueness. For example, the only social variable is population, which neglects other social conditions, such as poverty, education, and cultural heritage, which could affect transboundariness (they may or may not play a role in any specific aquifer). Sanchez and Eckstein (2017) were careful enough to present transboundariness as an approach, rather than as a metric or even as a concept by itself. The criteria developed attempt to consider a series of additional variables, apart from the hydrogeological conditions, with the purpose of expanding the existing perspective on transboundary aquifers.

Due to the impossibility of considering all possible variables, transboundariness should not be understood as an absolute measure or metric but as an indicator that other variables might be playing an important role in the agenda of the transboundary nature of an aquifer. The variable "other issues governing the agenda", though vague, is meant to indicate the need to consider additional criteria that could influence transboundariness and that might not have been considered in the proposed model.

The same reasoning applies to the prioritization scheme. The proposed priority ranks are also an indicator of a trend in the attention to and prioritization of some aquifers over others. If the prioritization of aquifers were divided into more than three ranks, the trend would be same. Transboundariness, then, should be understood as an indicator of a trend in the attention to and prioritization of some aquifers over others and not an absolute value.

We did not use a fixed criterion to identify the cities and communities in the border area, but generally they are cities and communities in Texas and Mexico and within 80 miles of the border. Given the limited information on groundwater and surface water use in some small overlying communities, groundwater dependency was scored based on the proxies of population, water well location, groundwater use, and surface water availability. More research will be required to assess the usefulness of this approach in other transboundary regions.

Likewise, the methodology has some limitations. The characterization of the hydrogeological units/aquifers by Sanchez et al. (2018) depends on limited information in some areas, and their characterization constitutes the base of this assessment. Therefore, the classification of those units for which there is limited information should be taken only as estimates, pending future research. The criteria of water quantity and quality challenges and groundwater dependency are based on reported data from the cities and communities located over the surface of the outcropping geological units, which confounds their implications for other regions that rely on the same unit for water but are located over the surface of a different unit.

This study applies to the stretch of the border between Mexico and Texas, and therefore considers only the bordering portion of the Rio Grande and its corresponding hydrogeological features, neglecting the upper Rio Grande basin and its headwaters in Colorado and New Mexico.

RESULTS

Based on their transboundariness scores, the hydrogeological units/aquifers were divided into three priority groups: Group 1, the highest priority; Group 2, medium priority; and Group 3, the lowest priority (Table 2, Fig. 2).

According to the level of transboundariness determined, the Valle de Juarez/Hueco–Tularosa Bolson, Conejos-Medanos/Mesilla Bolson, Edwards Aquifer, and BRB/Gulf Coast Aquifer are assigned first priority (Group 1). This is not surprising, considering that they are the only aquifers officially recognized as transboundary (International Groundwater Resources Assessment Centre IGRAC 2015). The same prioritization was also identified for the Palma Real-Guayabal/Laredo Fm. and the Yegua-Jackson and Allende-Piedras Negras Aquifers, which are not officially recognized as transboundary, but their socio-economic and political context give them high levels of transboundariness. This highlights the potential for more attention at the binational level in the coming years, considering the groundwater dependency of large urban centres as well as water quality challenges in this region.

Group 2 comprises those units of medium priority, considering their lower transboundariness scores. It is led by the Carrizo-Wilcox Aquifer, followed by the Presa La Amistad Aquifer, Catahoula Confining System, and Serrania del Burro Aquifer. Of this group, the Presa La Amistad and Carrizo-Wilcox Aquifers had the highest scores, with the highest probabilities of being given high

Table 2 Transboundariness of hydrogeological units/aquifers shared by Mexico and Texas

Aquifer or hydrogeologic unit	Criteria							
	Pop.	Groundwater dependency (for any use)	Water quantity/ quality challenges	Data/ research availability	Political recognition as transboundary	Cooperation efforts	Other issues governing the agenda	Total score
Conejos-Medanos/Mesilla B.	3	3	3	3	3	3	3	21
Valle de Juarez/Hueco–Tularosa B.	3	3	3	3	3	3	3	21
Red Light Draw B.	1	3	1	2	1	1	1	10
Green River Valley B.	1	3	1	2	1	1	1	10
Presidio B.	1	3	2	2	1	1	1	11
Redford B.	1	3	2	2	1	1	1	11
Cretaceous-Terlingua A.	1	1	2	1	1	1	1	8
Santa Fe del Pino A.	1	1	2	1	2	1	1	9
Serrania del Burro A.	1	3	2	1	2	1	1	11
Edwards A.	3	3	3	2	3	1	2	17
Eagle Ford Fm./Eagle Ford Group	1	3	1	1	2	1	2	11
Presa La Amistad A.	2	3	2	1	1	1	2	12
Allende-Piedras Negras A.	2	3	3	3	2	1	2	16
Escondido Fm./Escondido Fm.	1	2	1	1	1	1	1	8
Carrizo-Wilcox A.	3	3	2	2	1	1	1	13
Bigford Fm/Bigford Fm.	1	1	1	2	1	1	1	8
El Pico Clay Fm./El Pico Clay Fm.	3	1	2	1	1	1	1	10
Palma Real-Guayabal Fm./ Laredo Fm.	3	3	3	2	1	1	3	16
Yegua-Jackson A.	3	3	2	2	1	1	2	14
Catahoula Confining System	1	3	2	2	1	1	1	11
BRB/Gulf Coast A.	3	3	2	3	3	1	3	18

A. aquifer, *B.* bolson, *Fm.* formation

Transboundariness was measured in all hydrogeological units/aquifers except for those that did not report a significant pumping area, are constituted by igneous material and perform more as aquitards, or have complex geological heterogeneity that does not represent aquifer potential (Mariscal), plus those units that serve as barriers of other aquifer-type formations according to Sanchez et al. (2018). The criteria are adapted from Sanchez and Eckstein (2017)

priority in the near future in view of their strategic links to Amistad International Reservoir and the dependence of important urban centres on the Carrizo-Wilcox Aquifer. This group also comprises the Presidio and Redford Bolsons as interesting examples of current transboundariness. They show long-term potential to become high-priority aquifers, given the projected groundwater demand in the region, and therefore greater transboundariness in the future.

The lowest-priority group (Group 3) comprises the units with the lowest transboundariness scores. The two highest scores in this group are the Green River Valley and Red Light Draw Bolsons, which have significant aquifer potential in the long term. The socio-economic, environmental, and political context of the hydrological units/aquifers is addressed in the discussion section, next.

DISCUSSION

This section presents the situation in the border area, including the details that support the scores given to the various formations. It starts with the regional economic context, followed by analysis of groundwater dependency, water quantity and quality considerations, data and research availability, political recognition of the hydrogeological units/aquifers studied as transboundary, cooperation efforts on surface and groundwater, and finally other issues governing the agenda.

Regional economic context

In the transboundariness approach, economic activity is taken as directly proportional to population and

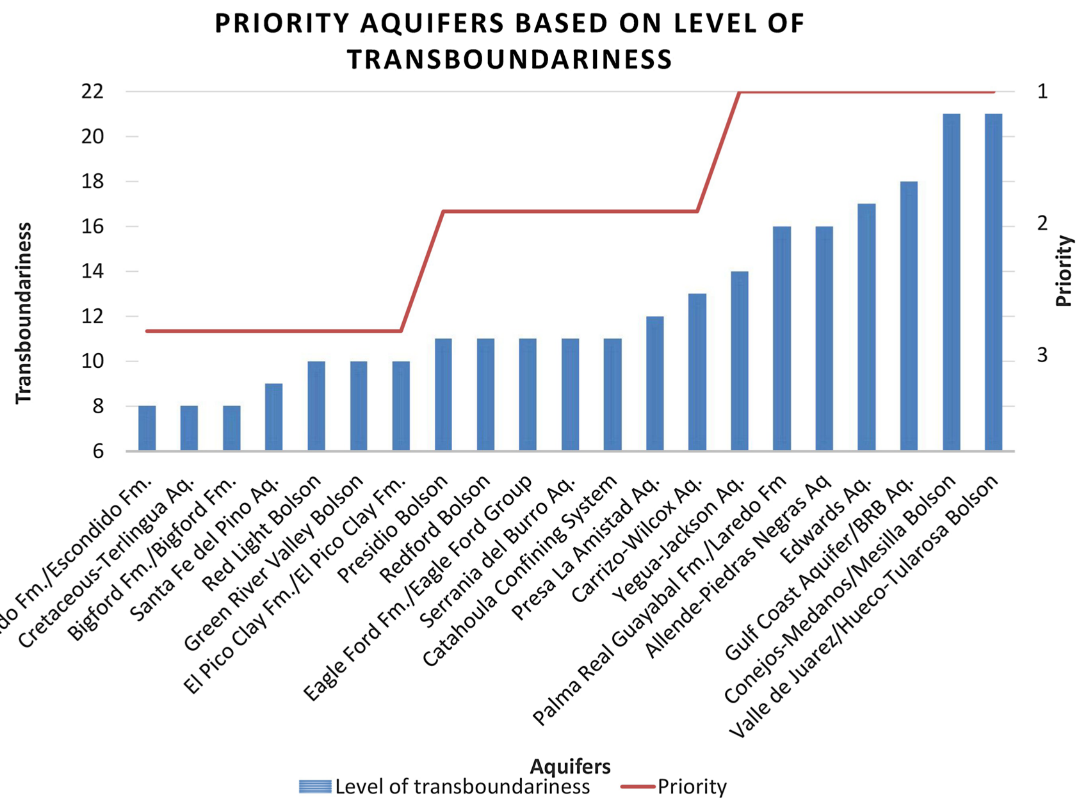

Fig. 2 Transboundariness and prioritization of hydrological units/aquifers shared by Mexico and Texas

groundwater dependency, so an independent economic measure was not required. However, consideration of the economic context was necessary to understand the socio-economic links.

On the border between Mexico and United States, *maquiladoras* have become a pole of attraction for migrants, driving urban and population growth. Between 2000 and 2010, population in the seven sister-city pairs along the border increased by 22%, from 4.4 to 5.4 million (Texas Commission on Environmental Quality 2017). One of the pairs is El Paso–Ciudad Juarez (overlying the Valle de Juarez/Hueco–Tularosa Bolson), the largest and fastest-growing cities in the region, with more than 2 million people, and with one of the largest numbers of maquiladoras (George et al. 2011).

Similarly, in the South Texas–Tamaulipas–Nuevo Leon–Coahuila region, the Laredo–Nuevo Laredo area (overlying the Palma Real-Guayabal Fm./Laredo Fm.) is the busiest commercial port of entry on the entire border. In this area, availability of shale resources presents new opportunities (overlying the Eagle Ford Fm./Eagle Ford Group), with southeast Texas, and also Tamaulipas, building infrastructure for energy production and trade (Van Schoik 2014). As a result of the shale gas development and lower electricity prices, U.S. exports to Mexico have grown faster than any other major U.S. export market. In the area of Laredo, 464 000 more trucks crossed the border in 2013 than in 2009 (Wilson and Lee 2014). Manufacturing and trade are said to have led the recovery in the United States and in Mexico from the Great Recession of 2007–2009 (Monge-Naranjo 2013).

Economic growth has not only brought benefits, but also increased social and environmental problems. The maquiladora industry has put enormous pressure on the fragile ecological environment, urban infrastructure, land and water resources, and all public services, increasing competition for access to natural resources and contributing to air, land, and water pollution (Strömberg 2002; Carrillo and Schatan 2005). Infrastructure is inadequate to handle the environmental impacts of population growth (primarily in the region overlying the BRB/Gulf Coast Aquifer) and industrial development along the border (International Boundary & Water Commission IBWC 2014). Regarding water resources, maquiladoras are not always major consumers of water but can be serious polluters, through discharges of hazardous or toxic waste into waterways or discharges that violate water quality standards (Carrillo and Schatan 2005; Sanchez et al. 2016).

Water availability constraints (in terms of both quantity and quality) have been identified as a risk factor for the economic and social dynamics of the border, affecting livelihoods and economic activities, including agricultural

irrigation and the maquiladora industry. Examples include Tijuana and Mexicali in Baja California and Ciudad Juarez in Chihuahua (SEMARNAT 2002). In Valle de Juarez, aquifer overdraft of 86 hm^3 $year^{-1}$ has been reported by CONAGUA (2015c).

Groundwater dependency

The Conejos-Medanos/Mesilla Bolson, Valle de Juarez/Hueco–Tularosa Bolson, and Yegua-Jackson Aquifer (Preston 2006) and the BRB/Gulf Coast Aquifer (Davidson and Mace 2006) are the main sources of water for their communities. In El Paso, the Valle de Juarez/Hueco–Tularosa Bolson provides 50% of the drinking water for the El Paso Water Utilities service area. The other 50% comes from the Rio Grande (International Boundary & Water Commission IBWC 2014). In contrast, Ciudad Juarez depends completely on the Valle de Juarez and Conejos-Medanos Aquifers for its municipal and industrial demands (Senate Reports 2006) and on surface water from the Rio Bravo and wastewater for irrigation (CONAGUA 2015c). Ciudad Juarez has recognized the limited ability of the Valle de Juarez Aquifer to supply future demands (TWDB 2016). The Allende-Piedras Negras Aquifer also represents an important source of water for the cities of Piedras Negras, Allende, Villa Union, Morelos, Zaragoza, Nava, and Guerrero on the Mexico side and Brackettville and Spofford on the Texas side. The sensitive surface–groundwater connection in this area, as well as the economic dependency of the mining industry on the Mexico side and irrigation on the Texas side, makes this aquifer a crucial groundwater system (Sanchez et al. 2016). There is also high dependency on the Carrizo-Wilcox Aquifer for urban and domestic uses in the cities of Carrizo Springs and Crystal City on the Texas side, and small communities on the Mexico side (such as Hidalgo), which use it for irrigated agriculture. The same level of groundwater dependency occurs in the area overlying the Palma Real-Guayabal Fm./Laredo Fm., as the sister cities of Laredo and Nuevo Laredo rely on this source for domestic and urban water supply (Lambert and Hartmann 1999), and to lesser extent the El Pico Clay Fm./El Pico Clay Fm.

The Edwards (Balcones Fault Zone) Aquifer, part of the Edwards Aquifer, provides water for approximately 2.5 million people in Austin and San Antonio in the U.S. and in the city of Acuña in Mexico. Like the Valle de Juarez/Hueco–Tularosa Bolson, the Edwards Aquifer is a crucial source of groundwater (Anaya 2001) for irrigation, followed by public supply, industry, mining, and thermoelectric power. Groundwater dependency is also reported in areas served by the smaller aquifers of the Trans-Pecos region of West Texas, including the Red Light Draw and Green River Valley Bolsons, which provide groundwater used mostly for livestock, and the Presidio and Redford Bolsons, which provide groundwater primarily used for domestic supply and irrigation on the Texas side. Considering that population growth and irrigation needs are projected to keep increasing the pressure on groundwater resources in this area (Sheng et al. 2001; Beach et al. 2008), the dependency in the communities surrounding the bolsons is considered high, even though there is more surface water available (Rio Conchos, Alamito Creek). Likewise, the sensitive ecosystems in the Chihuahua Desert (the *cienegas* and their native fishes) are highly dependent on groundwater (Sanchez et al. 2016). High dependency on groundwater resources, given the projections for future groundwater use, was also reported for the Serrania del Burro Aquifer (CONAGUA 2015a), Eagle Ford Fm./Eagle Ford Group (Bennett and Sayre 1962; Boghici 2002), and Presa La Amistad Aquifer (CONAGUA 2015b; Sanchez et al. 2016). Though population has decreased in the Serrania del Burro area, the aquifer is important given the growing demand on neighbouring aquifers, for which groundwater deficits are already reported (CONAGUA 2015a). Oil and gas production in the region of the Eagle Ford Fm./Eagle Ford Group makes this aquifer a strategic one in terms of dependency on natural resources, including groundwater, regardless of the aquifer potential, which is limited to local use and performs more as an aquitard. On the Mexico side, the community of Jimenez also relies on the aquifer for domestic use (REPDA 2015). As for the Presa La Amistad Aquifer, considering the strong surface and groundwater links to the Amistad Reservoir (Sanchez et al. 2016) and its recreation activities, which are associated with economic development in the region, groundwater dependency is reported as high; the Amistad National Recreation Area relies solely on groundwater (Larson et al. 2001; Purchase et al. 2001).

Water quantity and quality

The bordering stretch of the Rio Bravo/Rio Grande is 1255 miles long (the total length is approximately 1896 miles, including its headwaters in Colorado and New Mexico), and the whole basin covers approximately 335 000 square miles, with approximately half the basin in each country. It supplies water for drinking, industrial, and irrigation uses for more than 6 million people and 2 million acres of land, making water quantity and quality issues of the utmost importance for the border region and the surrounding area in U.S. and Mexico (U.S. Bureau of Reclamation 2017). Considering climate change predictions—more frequent El Niño events (Khedun et al. 2012)—and the over-allocated condition of the basin, groundwater could be an alternative to additional sources of water. The major water quality problems in the basin are salinity and bacterial

contamination. For example, river flows arriving in El Paso have a substantial salinity contribution from irrigation flow and municipal wastewater return in New Mexico, which can increase to over 1000 mg L^{-1} during May and September, depending on the actual irrigation demands (TWDB 2016). On the Mexico side, CONAGUA (2006) has reported faecal coliforms at some of the monitoring stations in the Rio Bravo/Rio Grande basin and contamination from return flows from 12 508 ha that are under irrigation (CONAGUA 2015c). And the Far West Texas Water Planning Group (2016) reports heavy metals and pesticides downstream from El Paso.

The water quality of the Edwards Aquifer is generally good, but depends on location (Land et al. 1992; George et al. 2011). Poorer groundwater quality is the result of evaporite beds in the Glen Rose limestone, surface contamination, and above-normal levels of radioactivity detected in sand sequences of the Glen Rose and Hensel Formations (TWDB 2016). East of the Pecos River, oil-field brines and agricultural runoff have degraded the groundwater quality in the northern portion of the Edwards Aquifer (George et al. 2011). In the Yegua-Jackson Aquifer, quality varies due to sediment composition in the formations (Preston 2006). In the Allende-Piedras Negras Aquifer there is good water quality in general on the eastern side, but in some areas the water is not fit for drinking due to sulphates and total dissolved solids, or use for irrigation is limited by high salinity (DOF 2011). In the Santa Fe del Pino Aquifer on the Mexican side, groundwater can be used for irrigation but usually not for drinking purposes due to total dissolved solids above 4000 ppm in some parts of the aquifer (DOF 2015). In the El Pico Clay Fm./El Pico Clay Fm., water quality is considered poor (brackish) (Clark 2016). In other places, such as the Escondido Fm./Escondido Fm. (Eagle Pass Water Works System 2015) and the Bigford Formation (City of Carrizo Springs 2014), water quality challenges have not been reported so far.

In the Edwards-Trinity (Plateau) and Gulf Coast Aquifers, contamination by radionuclides occurs naturally. In the Gulf Coast Aquifer, it is found in some wells in South Texas and in Harris County, where groundwater is used for municipal, industrial, and irrigation purposes. Subsidence is present in the counties of Harris, Galveston, and Fort Bend (George et al. 2011; Sanchez and Eckstein 2017). In the Winter Garden region of South Texas, irrigation is heavily dependent on the Carrizo-Wilcox Aquifer, which is being contaminated by leakages of saline water, as well as direct infiltration of oil-field brines from the surface (George et al. 2011).

According to Lambert and Hartmann (1999), the Gulf Coast, Laredo, and Carrizo Aquifers provide the best quality of water in sufficient yields for public supply and other uses. But all these aquifers have large concentrations of sodium, sulphate, and chloride, totalling more than 500 mg L^{-1} of dissolved solids. In the Gulf Coast Aquifer, arsenic, boron, and uranium have been found (Lambert and Hartmann 1999).

In the Laredo aquifer, which serves as the aquifer for a considerable part of Webb County (Lambert and Hartmann 1999), the salinity of water increases to the east and to the south, towards Laredo. Concentrations in water samples from this aquifer exceeded the maximum amount of sulphate allowed in drinking water by the Environment Protection Agency (EPA MCL) and EPA standards for chloride, fluoride, manganese, and iron (Lambert and Hartmann 1999). There are reports of high bromide and chloride concentrations in the Eagle Ford Fm./Eagle Ford Group (Hildenbrand et al. 2017), significant arsenic levels in the region of the Catahoula Confining System (Gates et al. 2011), and high salinity (due to return flows from irrigation) in the Presa La Amistad Aquifer (Larson et al. 2001).

The Red Light Draw Bolson supports domestic use and watering of livestock and wild game. Large-capacity wells in the Rio Grande alluvium supplied water to irrigate cotton fields in the 1950s and 1960s, but the farms in this area were abandoned in the 1970s. The Green River Valley Bolson was once used for irrigation, but now groundwater is produced for the watering of livestock or wild game (Darling and Hibbs 2001). There has not been much research on the four identified bolson aquifers (Red Light Draw, Green River Valley, Presidio, and Redford), but the literature seems to concur on the potential for groundwater development in this region and therefore the need to better understand its transboundary nature (Sheng et al. 2001; Beach et al. 2008).

Data and research availability

The TAAP aquifers, the BRB/Gulf Coast Aquifer, and the Allende-Piedras Negras Aquifer have reasonable data to confirm their transboundary nature. Those with some data, primarily on the Texas side, include the four bolsons, Edwards Aquifer, Eagle Ford Fm./Eagle Ford Group, Bigford Fm./Bigford Fm., Palma Real-Guayabal Fm./Laredo Fm., Yegua-Jackson Aquifer, Carrizo-Wilcox Aquifer, and Catahoula Confining System. For the rest of the hydrogeologic units, there are limited data on groundwater conditions and/or potential transboundary links.

Political recognition as transboundary

The TAAP aquifers, the Edwards Aquifer, and the BRB/Gulf Coast Aquifer are the only ones recognized internationally as transboundary by ISARM. However, there are

technical reports on the Texas side that recognize the transboundary linkages of the Allende-Piedras Negras Aquifer (Boghici 2002), and considering the uncertainty regarding the limits of the Edwards Aquifer on the Mexico side, there seems to be a technical assumption that both the Santa Fe del Pino and Serrania del Burro Aquifers are also transboundary, because they are geologically linked to the Edwards Aquifer (Boghici 2002). The Eagle Ford Fm./Eagle Ford Group is recognized as a strategic shale gas resource, but there is limited information on groundwater connectivity and therefore limited support for political recognition of a transboundary aquifer.

Cooperation efforts on surface and groundwater

With the support of bilateral environmental institutions such as the Commission for Environmental Cooperation (http://www.cec.org) and the North American Development Bank (http://www.nadb.org) as well as the EPA, infrastructure for wastewater treatment is being developed near the border. Implementation of municipal drinking water and wastewater infrastructure projects is supported by the Border Environment Infrastructure Fund funded by the EPA. Through this grant program, by 31 March 2017, more than US$ 84 million had been contracted for 25 active projects (NADB 2017). The U.S. and Mexican sections of the International Boundary and Water Commission are also helping border communities in Mexico improve the planning of wastewater systems so that they can be certified by the Border Environment Cooperation Commission and financed by the North American Development Bank. As a result, wastewater-system projects have been certified in Reynosa and Anapra in Tamaulipas, among other cities (TWDB 2016). Though these cooperation efforts are important at the binational level, they are limited to surface water. Except for the TAAP aquifers, on which reported cooperation efforts are limited to information exchange and joint research, there are limited data on groundwater cooperation in the great majority of the hydrogeological units/aquifers, including the Edwards and BRB/Gulf Coast transboundary aquifers. Some cooperation has been reported on the Presa La Amistad Aquifer, with communications mainly related to logistics and management of surface water deliveries from Amistad Reservoir (Larson et al. 2001).

Other issues governing the agenda

The last criterion for the transboundariness of an aquifer relates to other issues that play a role in the binational agenda, highlighting priorities other than transboundary groundwater vulnerability. The Valle de Juarez/Hueco–Tularosa Bolson and the Conejos-Medanos/Mesilla Bolson were considered priority aquifers under TAAP precisely because of the vulnerability of the population to important sources of groundwater contamination. Public health threats such as increasing levels of *E. coli* and salinity downstream on the Rio Grande play an important role in the binational agenda, engaging cooperation efforts at both local and binational levels (Sánchez et al. 2007). This same rationale has been documented in the negotiation of Minute 242 of the IBWC/CILA (International Boundary & Water Commission IBWC 1973), which imposes restrictions on the Yuma Aquifer as a result of high salinity in surface water deliveries from the Colorado River. With respect to the rest of the hydrogeologic units of interest, the Presa La Amistad Aquifer and surrounding cities are affected by climatic and legal uncertainties related to annual water deliveries from Mexico to Texas required by the 1944 treaty. Regarding the Allende-Piedras Negras Aquifer, the fact that mining (MICARE) and brewing (Grupo Modelo) companies are the main groundwater users in the region on the Mexico side has meant that groundwater research, cooperation, and management have been eroded by political pressure and driven by economic priorities (Sanchez et al. 2016; Sanchez and Eckstein 2017).

The Palma Real-Guayabal/Laredo Fm., the BRB/Gulf Coast Aquifer, and to a lesser extent the Yegua-Jackson Aquifer underlie important border and sister cities with a variety of other issues that have taken over the binational water agenda, such as security, immigration, illegal urban settlements, maquiladoras, irrigated agriculture, and trade. As for the Eagle Ford Fm./Eagle Ford Group, the importance of this geologic formation has more to do with transboundary oil and gas production in this region, and less with groundwater production. Finally, other issues governing the agenda of the Edwards Aquifer (Balcones Fault Zone) are mostly related to the supply of water for the inner part of the state of Texas, primarily the city of San Antonio, and its groundwater management, which is guided by the Edwards Aquifer Authority.

CONCLUSIONS

The transboundariness approach highlights important results. First, even with the limitations mentioned earlier, the assessment of transboundariness agrees with the current level of attention to transboundary hydrogeological units/aquifers in the region, providing a quantifiable metric system that could be replicated in other transboundary aquifers in the world. Second, this approach provides a holistic and integrative perspective for transboundary aquifer assessment that goes beyond the physical approaches. Therefore, this approach could provide transboundary management alternatives that consider contextual

dimensions and time scales in addition to the physical boundaries. Finally, this prioritization exercise expands the criteria currently used to prioritize transboundary aquifers (groundwater dependency and contamination vulnerability) into a more comprehensive regime that links groundwater to socio-economic and political aspects, that is, to the communities and their natural and social environments as a whole. The transboundariness approach is flexible enough to include more or fewer variables and their respective scores, and still be able to identify trends in attention to and prioritization of aquifers. But the complexity of the linkages that pertain to a transboundary groundwater system can only portray a trend rather than an absolute value.

The results of this study reflect not only how the transboundary aquifers shared by Mexico and Texas are being used (or neglected), at which scale and rate, but also the socio-economic, environmental, and political situations of the populations that depend on these vital resources for current and future development. Future research should include the analysis of sustainable groundwater scenarios for the high-priority aquifers as well as the development of transboundary governance schemes, to move toward managing transboundary aquifers in a truly binational way.

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