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Effective Transboundary Aquifer Areas: An Approach for Transboundary Groundwater Management

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Research Impact Statement: The effective transboundary aquifer areas approach is an alternative way to identify the priority area of an aquifer using pumping hot spots for a simpler and local-based transboundary groundwater management scenario.

ABSTRACT: The natural complexity, heterogeneity, and extent of transboundary aquifers around the world, have led to controversy over which method or criteria should be used to identify and delineate their boundaries. Currently, there is no standard methodology that aquifer-sharing countries can use to delineate the area of a transboundary aquifer. In the case of Mexico and Texas, Mexico uses administrative boundaries, whereas Texas uses geological boundaries. This paper proposes a method for delineation and prioritization of aquifers (or aquifer areas) called effective transboundary aquifer areas (ETAAs), which uses a combination of physical criteria (geological boundaries, topography, and hydrography) and the location and density of active water wells in the borderland between Mexico and Texas. This method identifies the area of priority (productivity area) in the aquifer using pumping patterns or *hot spots* regardless of the aquifer's surficial geological limits, therefore offering a more effective, local and practical management option at the transboundary level. Different geological features or pumping patterns will have different sizes and locations of ETAAs within the same aquifer. In West Texas, which is dominated by bolsons, the method produces limited options for ETAAs, whereas in South Texas in the easternmost border the identified ETAAs are more significant.

(KEYWORDS: transboundary aquifers; Mexico; Texas; groundwater management; aquifer areas.)

INTRODUCTION

The natural complexity, heterogeneity, and extent of transboundary aquifers around the world, have led to controversy over which method or criteria should be used to identify and delineate their boundaries. Currently, there is no standard methodology that aquifer-sharing countries can use to delineate the area of a transboundary aquifer. For example, in the case of the United States (U.S.) and Mexico, even though 11 aquifers have been recognized as transboundary by the Internationally Shared Aquifer Resources Management (ISARM) Initiative (IGRAC 2015), not all of them have been completely delineated. Additionally, different delineation methods are used on the two sides of the border depending on the aquifer-sharing regions. Mexico uses administrative boundaries, whereas Texas, Arizona, New Mexico, and California use a combination of geological and basin boundaries (Sanchez et al. 2016). Recent joint research under the Transboundary Aquifer

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Assessment Program (TAAP) on the Santa Cruz and San Pedro aquifers (shared between Arizona and Sonora) and, to a lesser extent, the Conejos-Medanos Aq./Mesilla Bolson and Valle de Juarez Bolson/Hueco-Tularosa Bolson aquifers (shared between Texas and Mexico), has added some clarity to the topic as binational teams are working together to provide joint assessments using common methodologies (Callegary et al. 2016). However, the delineation of the rest of the transboundary aquifers, both recognized and unrecognized, have received less attention, and the majority are still uncertain (IGRAC 2015).

In the border area between Texas and Mexico, the Valle de Juarez Bolson/Hueco-Tularosa Bolson and Conejos-Medanos Aq./Mesilla Bolson, the Edwards Aquifer, and the Bajo Rio Bravo (BRB)/Gulf Coast Aquifer, are the only four aquifers that have been recognized officially as transboundary by ISARM (Sanchez et al. 2016). However, even for these aquifers, the reported boundaries and the methods of aquifer delineation vary depending on the source, and in some cases, is not even clearly defined (e.g., Edwards Aquifer) (Sanchez et al. 2016). There is also limited information on the criteria used for data collection, and lack of assessments of their transboundary character. Recent research (Sanchez et al. 2018b) suggests there could be up to 21 transboundary aquifers between Mexico and Texas. This represents a challenge from a technical, institutional, and political perspective as groundwater becomes more strategically necessary on both sides of the border, and therefore this study could be an opportunity to develop and propose new, practical, and efficient strategies to deal with their transboundary character.

The purpose of this paper was to offer an alternative method to prioritize aquifers (or aquifer areas) according to pumping patterns or "hot spots" of groundwater productivity in the aquifers between Mexico and Texas, using geological boundaries, topography and hydrography, and location and density of active water wells. The paper uses the hydrogeological units/aquifers (HGUs) reported by Sanchez et al. (2018b), adding the topography (elevation) and major water features (rivers) in each HGU to provide complementary elements that explain the pumping pattern distribution at the surficial level. The "effective transboundary aquifer areas" (ETAAs) or hot spots are based on the location and density of active pumping wells in each HGU (see Figures 1–5).

The ETAA approach represents the *effective extent* of the HGU regardless of its surficial geology and differentiates units or groundwater hot spots from those areas where pumping is not reported, therefore prioritizing those areas of active productivity within the aquifer. In some cases, for example, the BRB/Gulf Coast Aquifer and the Edwards Aquifer, the unit's geological extension (central Texas or Louisiana border, respectively) does not provide feasible, practical scenarios for transboundary management given the amount of stakeholders and groundwater entities that would have to be involved (particularly on the Texas side) in a potential negotiation process. The proprietary groundwater rights system prevailing in the state of Texas and the contrastingly centralized groundwater management system in the Mexico side, do not offer realistic scenarios to promote transboundary management options at the complete geographical extent of all identified HGUs. With the exception of the bolsons on East Texas that comprise small geographical areas, and some small aquifers around the Edwards Aquifer zone, the majority of the HGUs located in the southernmost border of West Texas extend significantly into both countries. Therefore, this alternative approach has the potential to enable more efficient, effective transboundary groundwater assessments, management options at a more regional, and local scale.

The use of the term "effective" in this context refers to the location of an area or areas within the boundary of each HGU that reports a pattern of water wells as an indicator of groundwater productivity that can be differentiated from the rest of the geographical extent of the HGU. This analysis is based on the location of the water wells at a vertical scale (depth) of the corresponding HGU, regardless of the surficial geologic boundaries. There can be more than one ETAA within the same HGU (nationally or internationally). There can also be an ETAA that extends across more than one HGU's surficial boundary or no identifiable ETAA (no pumping pattern). For the purpose of this research, only the identified ETAAs that cross the international border are considered.

The value of this approach relies on the possibility of identifying a more local effective productivity area within the aquifer boundaries that could facilitate the transboundary management process with aquifer riparians. A similar approach has been used in the recent agreement of the Al-Sag/Al-Disi Aquifer, shared by Jordan and Saudi Arabia, where groundwater extraction and therefore management efforts have been limited to a specific delineated pumping area (Sümer 2015). Parallel efforts have been recently reported where "zooning" of transboundary aquifers or the identification of aquifer's "hot spots" has been used to identify priority areas of management in the Southern African Development Community (Fraser et al. 2018). Although these examples might differ from the paradigm of promoting a holistic basin management perspective, the call for local, small-scale approaches with specific and clear objectives has recently gained more attention, as they have proven to be more efficient in terms of reaching

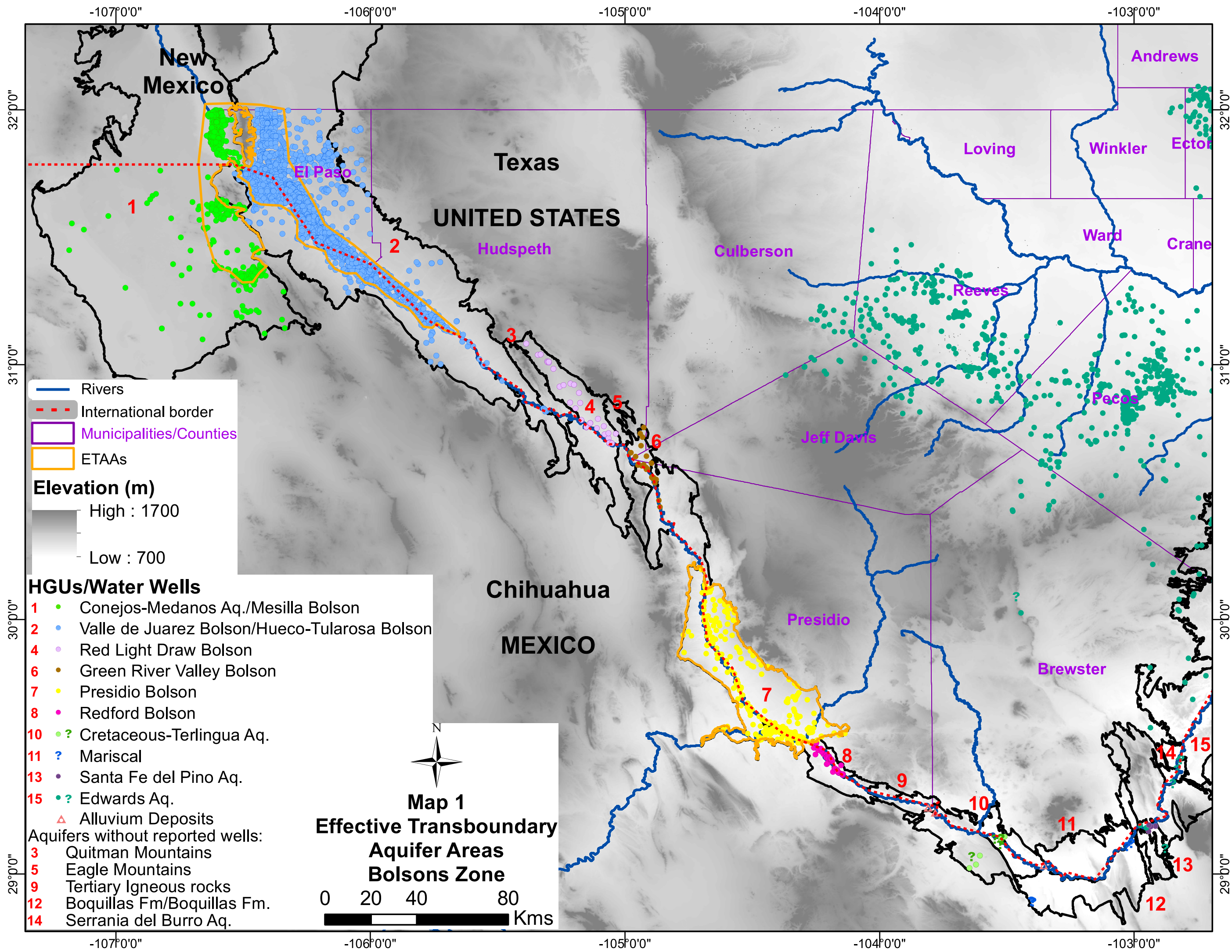

FIGURE 1. Effective transboundary aquifer areas (ETAAs): Bolsons zone. HGU, hydrogeological unit.

transboundary agreements or arrangement, compared to those proposed at binational or federal level (Concordia Municipality and EL Salto Municipal Quartermaster 2017; Sanchez and Eckstein 2017)

Although it is not the purpose of this study, this approach also reveals its potential to be applicable at domestic scale or within the countries boundaries. Additionally, the ETAA approach is not restricted to identifying ETAAs; it can also be used to develop prioritization schemes for the different geological areas of an aquifer considering water quality, water usage and amount of water extracted. In the present analysis and due to limited data on the region, we assume that these variables are constant, but it is worth noticing their potential for future research assessments.

The results of this paper show that in West Texas, which is dominated by the bolsons, the method produces limited options for ETAAs, whereas in South Texas in the easternmost side of the border, ETAAs identified are more relevant. The Carrizo-Wilcox, Laredo/Palma Real-Guayabal, Yegua Jackson, Allende-Piedras Negras, Bigford Fm./Bigford Fm, Lower Catahoula, and BRB/Gulf Coast Aquifers show the most significant ETAAs in the border area between Mexico and Texas.

METHODS

The identification of ETAAs is done over the geological extensions of the HGUs (HGUs with different geological properties that may have good or limited aquifer potential) reported by Sanchez et al. (2018b), adding the variables of topography, hydrological features (stream network), and well data (where available) in both sides of the border

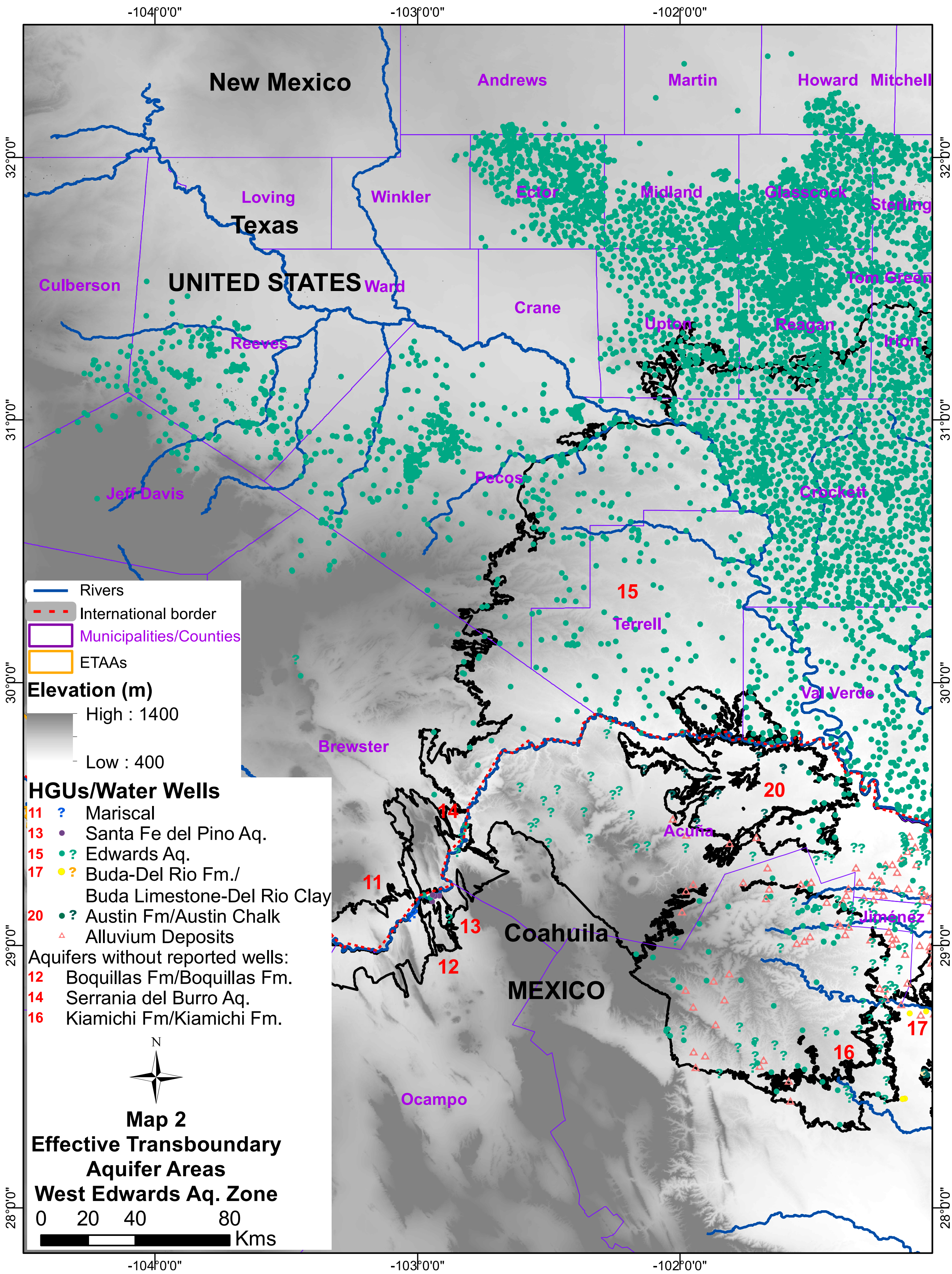

FIGURE 2. ETAAs: West Edwards Aquifer zone.

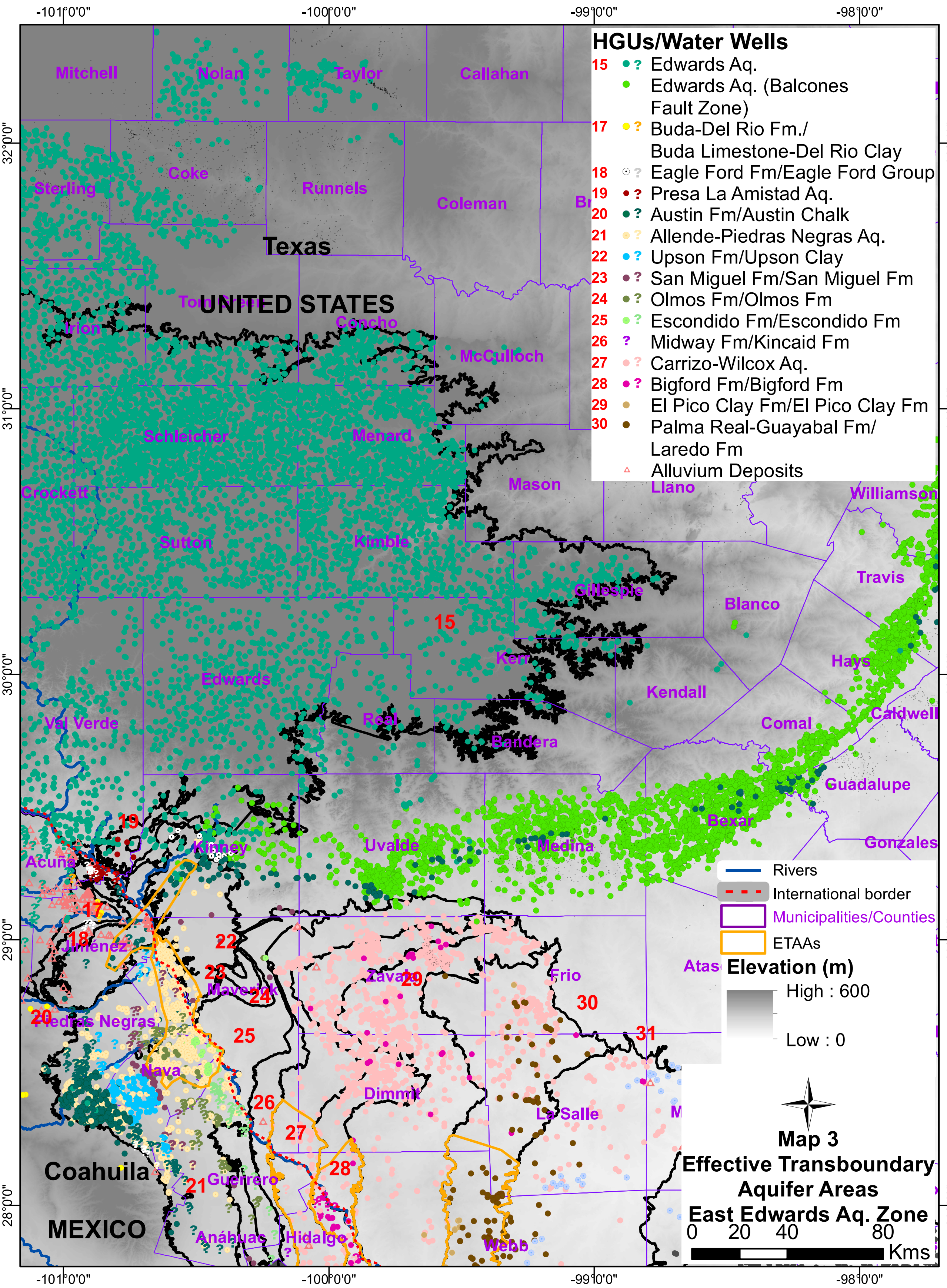

FIGURE 3. ETAAs: East Edwards Aquifer zone.

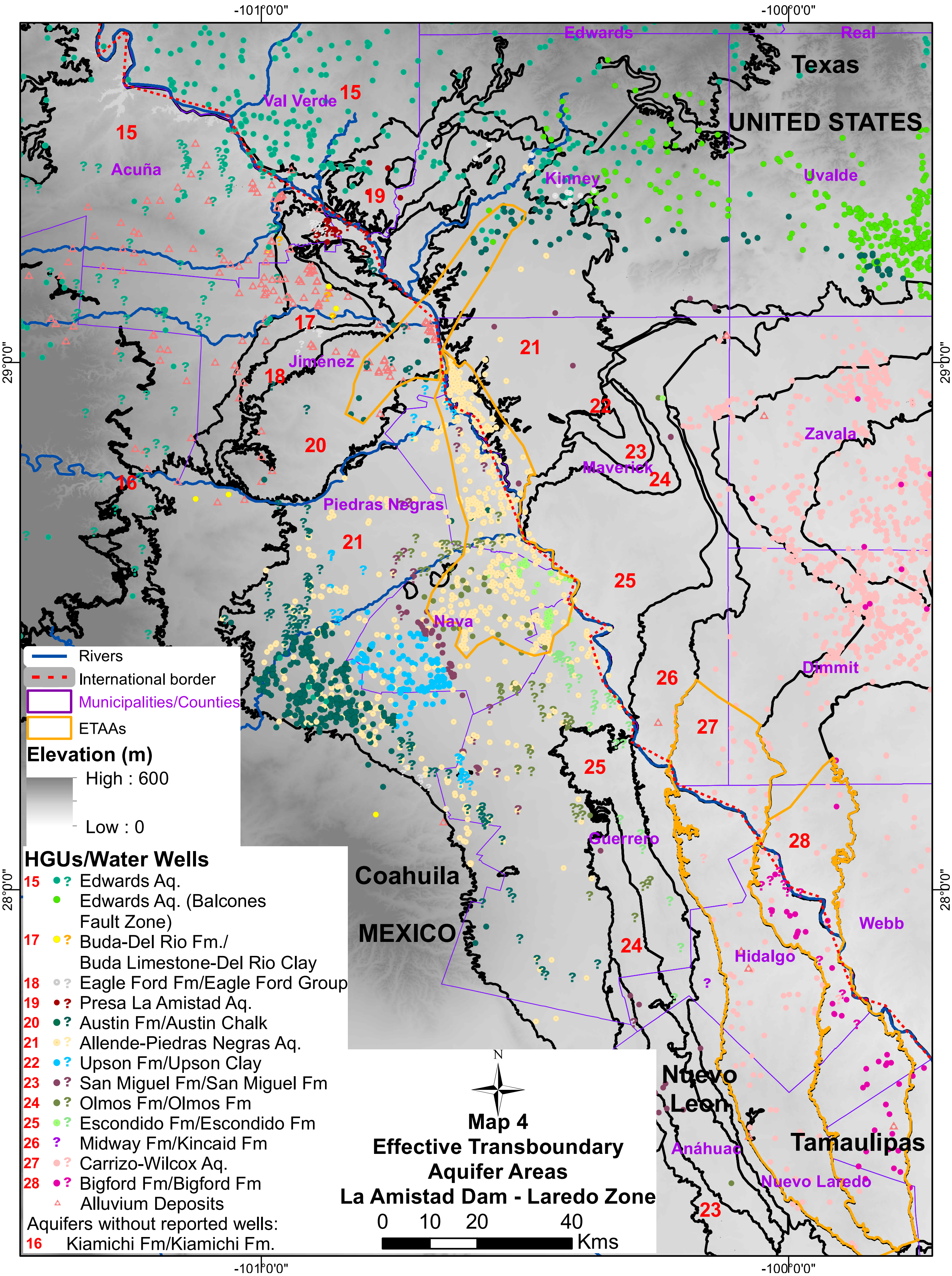

FIGURE 4. ETAAs: La Amistad Dam — Laredo zone.

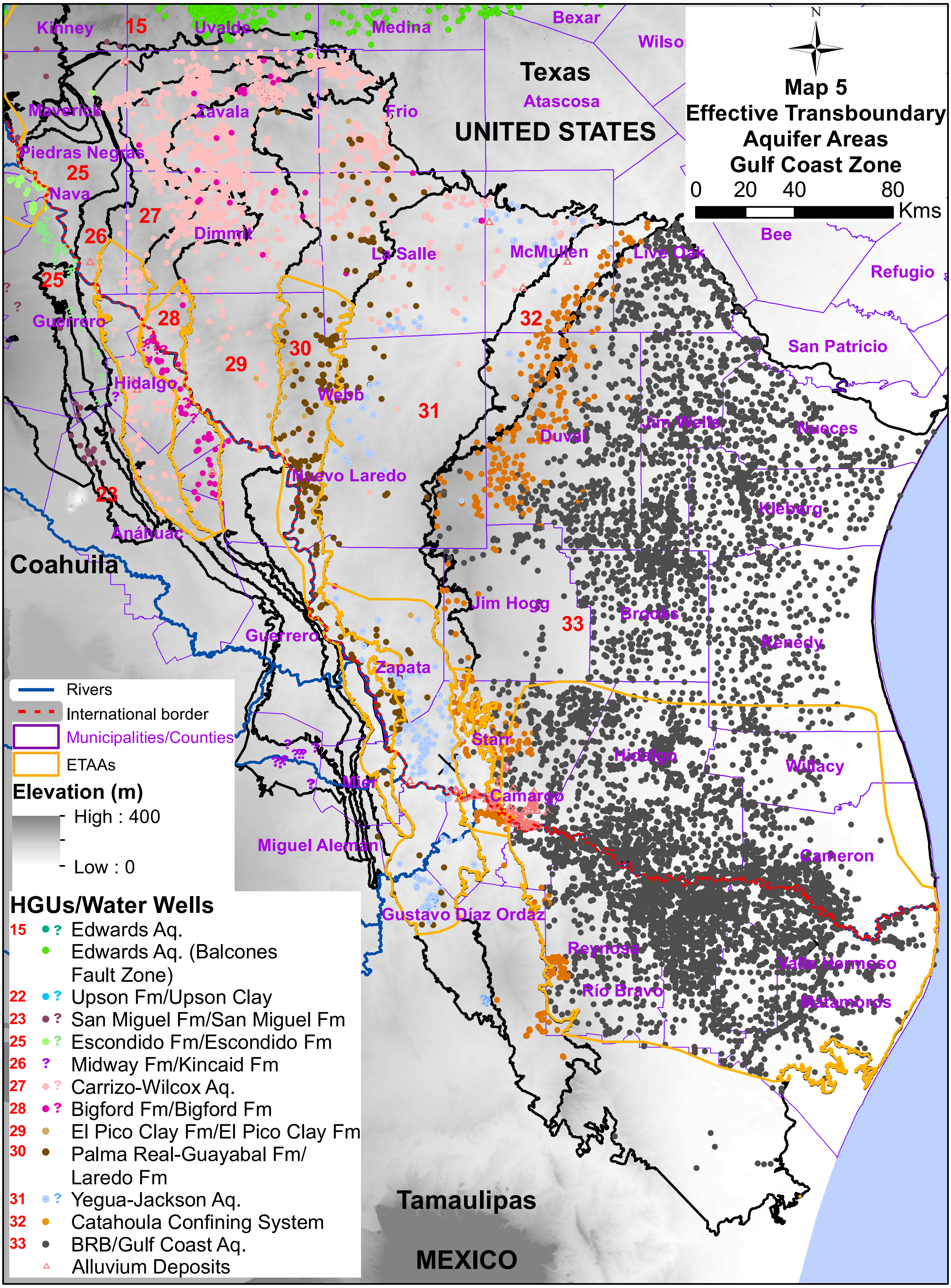

FIGURE 5. ETAAs: Gulf Coast zone. BRB, Bajo Rio Bravo.

between Mexico and Texas. In most HGUs in the border region, topography works as a water divide not only on the surface but also underground, so it can help define or confirm the boundaries of aquifers previously delimited using only structural geological features (King and Slichter 1899). Additionally, the hydrologic network has been incorporated to identify water divides according to the direction of flow.

The ETAA approach is primarily based on the understanding that due to the geological heterogeneity and changes in lateral facies, not all the aquifers' area is actually exploitable. Therefore, location, quantity, and depth of all available active wells are added to identify the exploitable, productive, hot spot, or pumping area of the aquifer. The study attempts to identify both: the active pumping areas of each unit and the geological boundaries of the units below the surface, thus adding a more refined level of vertical geological analysis to the one performed by Sanchez et al. (2018b).

The boundaries of the Conejos Medanos Aq./ Mesilla Bolson, Valle de Juarez Bolson/Hueco-Tularosa Bolson, Edwards Aquifer, and BRB/Gulf Coast Aquifer, which are transboundary aquifers officially recognized by both countries, were compared and analyzed using the ETAA approach to confirm or redefine their proposed official delimitations.

The topography data were obtained using digital elevation models (DEMs) from INEGI (Instituto Nacional de Estadistica y Geografia 2017) at a resolution of 120 m for the Mexican states of Chihuahua, Coahuila, Nuevo Leon, and Tamaulipas, and from the USGS (U.S. Geological Survey 2017) at a spatial resolution of 1/3 arc second for the state of Texas. The DEMs were grouped as a mosaic, and the elevation scales were scaled to match. In some cases, the vertical scale was visually exaggerated to show the detail of features on areas that seemed generally flat, as for example, for aquifers close to the Gulf of Mexico.

The stream network for the Mexico side was obtained from CONABIO (Maderey-R and Torres-Ruata 1990). And for Texas, the stream network was downloaded from the TCEQ (Texas Commission on Environmental Quality 2017).

Data on water wells on the Mexico side were obtained from Registro Publico de Derechos de Agua (REPDA 2015), and were downloaded in.KMZ format and separated by state. The downloaded well data for the states of Chihuahua, Coahuila, Nuevo Leon, and Tamaulipas include total depth, type of well, water use, and status (active or inactive). Information about the geological formation from which the well is drawing was not available. Therefore, well depth and lithological data were used as a proxy for geological unit data on the Mexico side. Well data for the Texas side were obtained from the Texas Water Development Board (TWDB) and BRACS (TWDB 2017). In most cases, these data include the geological unit from which water is extracted. The integrated well database was complemented with datasets provided by the U.S. Environmental Protection Agency (USEPA), CONAGUA, Lesser & Associates, and additional private industries for the Mexico side.

Groundwater simulation models from TWDB were also used to confirm and compare the proposed ETAAs for the Carrizo-Wilcox aquifer (southern portion) (Deeds et al. 2003), Yegua-Jackson aquifer (Deeds et al. 2010), and Gulf Coast Aquifer (Chowdhury and Mace 2007). The compiled data were analyzed using GIS tools for visualization of the ETAAs.

Wells are coded by color in Figures 1–5. The colors represent the formations from which water is being extracted. Colored question marks represent wells for which there is not enough depth information to confirm the geological formation from which water is drawn. However, based on the lithology and location of the well, we consider it a likely source.

Due to the different data sources, heterogeneity in units, different geographical coordinates and lack of information fields, it was necessary to reconcile parameters to be able to integrate the information and generate the visualization maps. Some datasets were georeferenced to local and others to planar coordinate systems. Therefore, the first step of this process was to convert geographic coordinates where necessary. The second step was to convert the well depths provided by TWDB from feet to meters. The third step was to integrate all the data into a new, unique database using the available information fields. A total of 36,432 wells were compiled in the transboundary area of interest, with 6,418 on the Mexico side and 30,014 on the Texas side. Of the total of wells, 2,357 were eliminated because their reported water sources were deeper than the areas of interest. This means that they are probably tapping nontransboundary aquifers. Also discarded were those wells used for oil and gas activities (except for rig wells), as well as those marked as plugged, destroyed, or inactive.

After integrating the database, fields were added to clean and sort the data. First, an aquifer code was assigned to each well based on the original database where such information was provided. Wells that did not have any aquifer assigned were compared with the surrounding wells. If a well with no aquifer code had a similar depth to surrounding wells with a known aquifer code, the well was assigned the neighbors' aquifer code. If it did not have surrounding wells with known aquifer codes, it was assigned the aquifer code of the geographical location and the matching HGU on the surface. In these cases, a question mark was added after the aquifer code. Another way to assign aquifer codes was to compare the depth of the well to the geologic cross sections (Undisclosed information). After estimating the depth of the geological formation in the cross section, wells of a similar depth in those areas would presumably access the same geological formation. At this point, only 1,066 wells of the 34,075 had neither depth information nor an aquifer code. For these cases, a code was assigned depending only on the geographical location and its surficial geology, and it was tagged with a question mark as well.

A special case arose with alluvial shallow wells located over a formation on the surface but for which there was neither confirmation of their interactions with the formations below, nor well-depth data. However, considering the cross-formational flow between alluvium and underlying formations, as described by Sanchez et al. (2018a), it is plausible that these alluvial deposits are connected to the formation they lie above. These wells are represented in the figures with triangles and labeled as alluvial deposits.

Given the limited data, particularly on the Mexico side, this study reaches important assumptions. First, groundwater flow is not considered, therefore neither are cones of depression (where the normal groundwater flow is disrupted in the surrounding area of a pumping a to gradient differences between the water table and the water in the well) (Theis 1938). Second, lithology of each aquifer is homogeneous across the unit. Third, all the groundwater pumped from the reported wells in both countries is accurately reported by the corresponding institution. Type of water use, water quality, and the amount of water extracted per well is not considered, so all the wells have the same level of significance.

Table 1 presents a compilation of the ETAAs characteristics performed on all HGUs/aquifers reported by Sanchez et al. (2018b), 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). Additionally, those units that serve as barriers of other aquifer-type formations according to Sanchez et al. (2018b) are also not considered. However, all reported units are included in the corresponding figures for visual reference. It is worth mentioning that each HGU in Table 1 maintains their original ID given by Sanchez et al. (2018b), therefore they do not follow a consecutive ID order. The criteria and reported coding of the variables of population and groundwater dependency were obtained from Sanchez et al. (2018a) where "3" represents population >400,000 inhabitants, "2" represents population between 100,000 and 400000, and "1" represents population with <100,000 inhabitants and it is based on the total area of the HGU. The criteria for groundwater dependency (any use) is "3" for groundwater dependency >70%, "2" between 40%–60%, and "1" for <30% groundwater dependency and it is also based on the total area of the HGU.

For the purpose of this research, the terms "aquifer" or "HGU" are used alternatively to refer to the same concept regardless of aquifer potential and water quality.

RESULTS

Figures 1 through 2 show the HGUs according to Sanchez et al. (2018a) from the western side of the state of Texas to the Gulf of Mexico. The figures show HGU delineation, elevation, major rivers, water wells and border municipalities and counties. Each figure shows the well pattern in each formation within and across the different HGUs represented as a cluster of dots of the same color. The purpose of these figures is to analyze four important elements: the agreement of the geological delineation with topography and major water features (rivers); the HGUs from which the wells are extracting water, regardless of their surface location; pumping patterns (based on the previous two elements); and finally the ETAAs.

Table 1 shows a compilation of the results described below, along with the total area of the unit compared to the ETAAs' area (in each country), number of wells (total and within the ETAAs), depth of wells (range), geological features according to Sanchez et al. (2018b) and primary groundwater use. The Table also includes the criteria used by Sanchez et al. (2018a) to account for population and groundwater dependency to complement the analysis.

ETAAs in the Bolsons Area

Figure 1 shows the HGUs in the Bolsons area. With sparse population and limited research with just few hydrogeological studies, east of the Valle de Juarez Bolson/Hueco-Tularosa Bolson, water wells in this area are used primarily for livestock and domestic supply. They are located mostly in the shallowest alluvial part of the HGU and within the identified geological and topographical boundaries (TWDB 2017). In this region, considering the geological and lithological features of the bolsons, the pumping pattern seems to be circumscribed by the natural boundaries of the corresponding HGU at the surface level;

TABLE 1. Compilation of Data of HGUs and identified ETAAs (adapted from Sanchez et al. 2018a, 2018b). Criteria for population codes: 3: >400,000, 2: 100,000–400,000, 1: <10-0,000. Criteria for GW dependency (any use): 3: >70%, 2: 40%–60%, 1: <30%

ID	Aquifer	Geological units (Mexico/Texas)	Geologic age	Water use	Depth/# wells in HGU	HGU Area	Depth[1]/# wells in ETAA	ETAA area/well density	GW dependency (HGU)	Pop. (HGU)
1	Conejos-Medanos Aq./Mesilla Bolson Aq.	Qt Alluvium/Qt Alluvium Qt Lacustrine/Qt Lacustrine Qt Conglomerates/Qt Conglomerates Qt Eolic/Santa Fe Group Qt to Tertiary clay and mud (USA)	Pleistocene-Holocene Pleistocene-Holocene Pleistocene-Holocene Oligocene-Pleistocene Neogene-Pleistocene	Livestock domestic	0–368 m 443 wells	10,550 km^2 (Mex = 76% USA = 24%)	0–368 m 394 wells	1,355 km^2 (Mex = 39% USA = 61%) 0.29 wells per km^2	3	3
2	Valle de Juarez Bolson/Hueco-Tularosa Bolson	Qt Alluvium/Qt Alluvium Qt Eolic (Mex) Qt Conglomerates/Qt Conglomerates Neogene conglomerate (Mex) Qt to Tertiary clay and mud (USA)	Pleistocene-Holocene Pleistocene-Holocene Pleistocene-Holocene Neogene Neogene-Pleistocene	Livestock domestic	0–749 m 1,546 wells	11,852 km^2 (Mex = 27% USA = 73%)	0–366 m 1,334 wells	1,925 km^2 (Mex = 34% USA = 66%) 0.69 wells per km^2	3	3
4	Red Light Draw Bolson	Qt Alluvium/Qt Alluvium Qt Conglomerates/Qt Conglomerates Neogene conglomerate (Mex) Qt to Tertiary clay and mud (USA)	Pleistocene-Holocene Pleistocene-Holocene Neogene Neogene-Pleistocene	Livestock domestic	0–160 m 18 wells	1,293 km^2 (Mex = 47% USA = 53%)	—	—	1	3
6	Green River Valley Bolson	Qt Alluvium/Qt Alluvium Qt Conglomerates/Qt Conglomerates Neogene conglomerate (Mex) Qt to Tertiary clay and mud (USA)	Pleistocene-Holocene Pleistocene-Holocene Neogene Neogene-Pleistocene	Livestock domestic	0–109 m 12 wells	471 km^2 (Mex = 65% USA = 35%)	—	—	1	3
7	Presidio Bolson	Qt Alluvium/Qt Alluvium Qt Conglomerates/Qt Conglomerates Neogene conglomerate (Mex) Qt to Tertiary clay and mud (USA)	Pleistocene-Holocene Pleistocene-Holocene Neogene Neogene-Pleistocene	Livestock domestic urban	0–201 m 352 wells	2,469 km^2 (Mex = 37% USA = 63%)	2–201 m 352 wells	2,469 km^2 (Mex = 37% USA = 63%) 0.14 wells per km^2	1	3

(continued)

Table 1. (continued)

ID	Aquifer	Geological units (Mexico/Texas)	Geologic age	Water use	Depth/# wells in HGU	HGU Area	Depth[1]/# wells in ETAA	ETAA area/well density	GW dependency (HGU)	Pop. (HGU)
8	Redford Bolson	Qt Alluvium/Qt Alluvium	Pleistocene-Holocene	Livestock domestic	0–122 m 27 wells	394 km^2 (Mex = 78% USA = 22%)	—	—	1	3
		Qt Conglomerates/Qt Conglomerates	Pleistocene-Holocene							
		Neogene conglomerate (Mex)	Neogene							
		Qt to Tertiary clay and mud (USA)	Neogene-Pleistocene							
10	Cretaceous-Terlingua Aq.	Javelina Fm. (USA)	Maastrichtian	Urban industrial irrigation livestock	6–42 m 9 wells	863 km^2 (Mex = 72% USA = 28%)	—	—	1	1
		Aguja Fm./Aguja Fm.	Maastrichtian							
		Pen Fm./Pen Fm.	Coniacian-Santonian							
		Santa Elena Fm./Santa Elena Limestone	Albian — Cenomanian							
13	Santa Fe del Pino Aq.	Qt Alluvium/Qt Alluvium	Pleistocene-Holocene	Domestic recreation	12–30 m 4 wells	101 km^2 (Mex = 85% USA = 15%)	—	—	1	1
		Qt Conglomerates/Qt Conglomerates	Pleistocene-Holocene							
14	Serrania del Burro Aq.	Qt Alluvium/Qt Alluvium	Pleistocene-Holocene	No reported wells	0	115 km^2 (Mex = 42% USA = 58%)	—	—	1	3
		Qt to Tertiary clay and mud (USA)	Neogene-Pleistocene							
15	Edwards Aquifer	Devils River Limestone (USA)	Albian — Cenomanian	Livestock, agriculture urban	0–1,069 m 11,446 wells	98,742 km^2 (Mex = 21% USA = 79%)	—	—	3	3
		Santa Elena Fm./Santa Elena Limestone	Albian — Cenomanian							
		Salmon Peak Fm./Salmon Peak Limestone	Albian							
		McKnight Fm./McKnight Fm.	Albian							
		West Nueces Fm./West Nueces Fm.	Albian							
		Edwards Fm./Edwards Fm.	Albian							
		Aurora Fm./Glen Rose Fm.	Albian							
18	Eagle Ford Fm./Eagle Ford Group	Eagle Ford Fm./Eagle Ford Group	Cenomanian-Turonian	Agriculture domestic	6–150 m 32 wells	584 km^2 (Mex = 68% USA = 32%)	—	—	1	3
19	Presa La Amistad	Qt Alluvium/Qt Alluvium	Pleistocene-Holocene	Livestock domestic urban	6–40 m 20 wells	618 km^2 (Mex = 16% USA = 84%)	—	—	2	3
		Uvalde Gravel (USA)	Pliocene-Pleistocene							

(continued)

Table 1. (continued)

ID	Aquifer	Geological units (Mexico/Texas)	Geologic age	Water use	Depth/# wells in HGU	HGU Area	Depth[1]/# wells in ETAA	ETAA area/well density	GW dependency (HGU)	Pop. (HGU)
20	Austin Fm./ Austin Chalk	Austin Fm./Austin Chalk	Coniacian-Santonian	Agriculture urban	0–300 m 540 wells	5,019 km^2 (Mex = 82% USA = 18%)	12–120 m 34 wells	531 km^2 (Mex = 54% USA = 46%) 0.06 wells per km^2	3	1
21	Allende-Piedras Negras Aq.	Qt Alluvium/Qt Alluvium Qt Conglomerates/Qt Conglomerates Uvalde Gravel (USA)	Pleistocene-Holocene Pleistocene-Holocene Pliocene-Pleistocene	Livestock agriculture urban	0–100 m 775 wells	9,109 km^2 (Mex = 77% USA = 23%)	3–45 m 486 wells	1,168 km^2 (Mex = 82% USA = 18%) 0.42 wells per km^2	2	3
25	Escondido Fm./ Escondido Fm.	Escondido Fm./Escondido Fm.	Maastrichtian	Agriculture domestic	27–161 m 65 wells	2,370 km^2 (Mex = 32% USA = 68%)	—	—	1	2
27	Carrizo-Wilcox Aq.	Carrizo Fm/Carrizo Sand Wilcox Fm./Indio Fm.	Eocene Eocene	Agriculture industrial rig	0–1,914 m 1,627 wells	6,622 km^2 (Mex = 55% USA = 45%)	10–180 m 89 wells	2,225 km^2 (Mex = 77% USA = 23%) 0.04 wells per km^2	3	3
28	Bigford Fm./ Bigford Fm.	Bigford Fm./Bigford Fm.	Eocene	Domestic livestock	30–579 m 76 wells	4,660 km^2 (Mex = 39% USA = 61%)	7–153 m 50 wells	1,634 km^2 (Mex = 74% USA = 26%) 0.03 wells per km^2	1	1
29	El Pico Clay Fm./El Pico Clay	El Pico Clay Fm./El Pico Clay	Eocene	Industrial domestic	0–597 m 16 wells	7,395 km^2 (Mex = 15% USA = 85%)	—	—	3	1
30	Palma Real-Guayabal Fm./Laredo Fm.	Palma Real-Guayabal Fm./Laredo Fm.	Eocene	Livestock agriculture	0–830 m 227 wells	8,854 km^2 (Mex = 20% USA = 80%)	4–304 m 158 wells	4,045 km^2 (Mex = 78% USA = 22%) 0.04 wells per km^2	3	3
31	Yegua-Jackson Fm.	Yegua Fm./Yegua Fm. Jackson Fm./Jackson Group	Eocene Eocene	Livestock domestic industrial	0–411 m 158 wells	15,950 km^2 (Mex = 18% USA = 82%)	7–213 m 115 wells	4,261 km^2 (Mex = 43% USA = 57%) 0.03 wells per km^2	3	3
32	Catahoula Confining System	Catahoula-Vicksburg Fm. undivided Catahoula Fm./ Catahoula Fm. Vicksburg Fm./Vicksburg Fm. Frio Fm./Frio Fm.	Oligocene-Miocene Oligocene-Miocene Oligocene Oligocene	Livestock industrial agriculture	0–701 m 434 wells	6,837 km^2 (Mex = 46% USA = 54%)	45–157 m 52 wells	850 km^2 (Mex = 25% USA = 75%) 0.06 wells per km^2	1	3

(continued)

Table 1. (continued)

ID	Aquifer	Geological units (Mexico/Texas)	Geologic age	Water use	Depth/# wells in HGU	HGU Area	Depth[1]/# wells in ETAA	ETAA area/well density	GW dependency (HGU)	Pop. (HGU)
33	BRB/Gulf Coast Aquifer	Qt Alluvium/Qt Alluvium	Pleistocene-Holocene	Agriculture industrial domestic	0–1,114 m 6,032 wells	60,652 km^2 (Mex = 29% USA = 71%)	4–776 m 4,282 wells	24,947 km^2 (Mex = 49% USA = 51%) 0.17 wells per km^2	3	3
		Qt Lacustrine/Qt Lacustrine	Pleistocene-Holocene							
		Beaumont Fm./Beaumont Fm.	Pleistocene							
		Lissie Fm. (USA)	Pleistocene							
		Reynosa Fm./Goliad Fm.	Pliocene							
		Oakville-Lagarto Fm./Flemming Fm.	Miocene							
		Catahoula Fm./Catahoula Fm.	Oligocene-Miocene							

Notes: Table includes all HGUs/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. (2018b). The criteria for population (Pop.) and groundwater dependency (GW dependency) are adapted from Sanchez et al. (2018a) and are based on the total area of the corresponding HGU.

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

[1]Depth of wells within the ETAAs might differ from the depth of wells of the total HGU.

therefore, there is limited differentiation in priority within the area of the HGUs. Topography and pumping patterns confirm the geological boundaries of the Conejos-Medanos Aq./Mesilla Bolson and Valle de Juarez Bolson/Hueco-Tularosa Bolson Aquifers (Hibbs et al. 1997), aligning them with the official boundaries recognized by ISARM and reported by the TAAP (Alley 2013). Most of the water is reported as being extracted from the bolsons and from what is called the Rio Grande Basin (TWDB 2017). A few wells also draw from Quaternary Clay and Mud deposits, producing mainly brackish water. Groundwater in this region is mainly used to supply urban needs for the cities of Ascención, Juarez, and Ahumada on the Mexico side, and Las Cruces (New Mexico) and El Paso (Texas) on the U.S. side. Pumping on the Mexico side of the Conejos-Medanos Aq./Mesilla Bolson is considered sporadic and not significant (CONAGUA 2015a). Apart from these two aquifers and the Presidio Bolson, the rest of the bolsons and the other HGUs shown in Figure 1 do not seem to have a significant pumping area worth redefining into an ETAA (see Table 1 for compiled details).The Quitman Mountains, Eagle Mountains, and Mariscal and Tertiary Igneous Rocks were not considered in the analysis given their negligible role as aquifer material (a couple of shallow water wells on the boundaries of the formations).

Although the ETAAs of the Valle de Juarez Bolson/Hueco-Tularosa Bolson and Conejos-Medanos/Mesilla Bolson are not different from the original hydrogeological boundaries, it is important to highlight that the boundaries proposed on this study for the Mexico side do not coincide with those reported by CONAGUA, which uses a combination of physical and administrative boundaries to delineate aquifers (IGRAC 2015; CONAGUA 2015c). The boundaries developed in this study for these aquifers do coincide with those reported on the Texas side. The rest of the HGUs identified in Figure 1, apart from the Redford and Presidio Bolsons (Wade and Jigmond 2013) are not very well studied. In addition, as noted, the two countries use different criteria to delineate aquifer boundaries.

There are no ETAAs proposed for the Red Light Draw Bolson, Green River Valley Bolson, or Redford Bolson as only few wells are reported from both sides of the border. There is only one well reported on the Mexico side from the Green River Valley Bolson, and nine from the Redford Bolson. The few wells reported on the Texas side are used for livestock and domestic needs. The Redford Bolson reports some wells on the Texas side that extract groundwater, from approximately 2 m (close to the Rio Grande) to 120 m in depth, mostly from igneous material (Groat 1972; TWDB 2017). On the Mexico side, well depths are approximately 10 m and reported to be drawing from the Rio Conchos basin in the alluvial region. Groundwater is used mostly for urban and domestic supply for Ejido Barranco Azul (REPDA 2015).

According to TWDB groundwater modeling reports, the boundaries of the Presidio Bolson and Redford Bolson on the Mexico side include the limestone and shale material in the southern part of the formation mainly as boundary layers, but also for the potential groundwater recharge flow of these formations into the aquifer (Wade and Jigmond 2013). Given the approach of this study and the lack of data to confirm geological boundaries on the Mexico side, we limit the aquifer boundaries to the basin fill (Quaternary Alluvium). The Presidio Bolson (Quaternary alluvium and Quaternary to Tertiary deposits) is recharged mostly from the Rio Conchos basin on the Mexico side and from Alamito Creek on the Texas side. Water is extracted from the bolson, the Rio Grande basin (alluvial deposits), and occasionally from the igneous rocks underneath the bolson at depths between 2 and 352 m (Groat 1972; Gabaldón 1991). According to the pumping pattern, there is an ETAA within the boundaries of the surficial geology of the aquifer, with a total of 352 reported wells; however, the applicability of the ETAA approach to this HGU is limited because there is no clear differentiation of priority areas within the aquifer. Water is used mostly for livestock and domestic needs on the Texas side and urban use on the Mexico side. This bolson underlies the largest border cities in the area of the West Texas Bolsons: Presidio (Texas) and Ojinaga (Chihuahua).

The Cretaceous-Terlingua Aquifer has some water wells reported on both sides of the border. Some of the wells draw groundwater from the Santa Elena Formation (part of the Edwards Aquifer) at a depth of around 300 m, and the rest from the alluvial Rio Grande Basin at depths of 6 to 40 m (TWDB 2017). Water is used for urban supply, industry, and irrigation (Fallin 1990). On the Mexico side, a few wells draw water from the alluvial deposits at shallower depths (6–15 m), and it is used for livestock in the Ejido Manuel Benavides. The San Carlos and San Antonio Rivers drain the region before they discharge into the Rio Grande.

The last two HGUs of interest in Figure 1 are the Santa Fe del Pino and Serrania del Burro Aquifers. Even though geologically both aquifers are considered part of the Santa Elena Formation, which is also part of the Edwards Aquifer, their geological features and the transboundary linkages in the area (the only ones with significant Quaternary content) distinguish them as separate units. For the Santa Fe del Pino Aquifer, the boundaries are surrounded by limestone, and they agree with the topography. Wells are located in the boundaries of the formation at 30–50 m depths on the Texas side (TWDB 2017), and the water is used mostly for urban consumption and recreation as natural warm springs (Big Bend National Park and the municipalities of Ocampo, Santa Elena, and Maderas del Carmen on the Mexico side). No wells are reported as drawing from the Serrania del Burro Aquifer. The water wells identified at the edge of the river have recorded depths between 180 and 200 m, and therefore they draw from the Edwards Aquifer. There are no wells identified on the Texas side, and the few on the Mexico side are used for urban water supply for the municipalities of Acuna, Ocampo, and Muzquiz and as natural springs (CONAGUA 2015b). It is worth recalling that the surface water in this region that discharges into the main stem of the Rio Grande is mainly fed from springs, which are deeply connected to groundwater in this region. Therefore, the recharge zones in the mountain region around this area, on both sides of the border, are considered sensitive areas for protected native ecosystems that deserve attention (Sanchez et al. 2016). Considering the limited number of wells reported from both sides of the border, no ETAAs have been identified for these HGUs.

ETAAS in the West Edwards Aquifer Zone

Figure 2 shows the western zone of the Edwards Aquifer and its corresponding HGUs. Considering the extension of the Edwards Aquifer on the Mexico side as well as the geological (faults and lineaments) and topographic features in the area and the random distribution of water wells (no clear pattern detected), there is no ETAA identified in this region. The significant differences in data availability and research between the Edwards Aquifer on the Texas side vs. the Mexico portion of the aquifer do not provide confidence in the location of the physical boundaries of the aquifer on the Mexico side. In fact, even though the Edwards Aquifer is recognized as transboundary by the ISARM, details of the boundaries of the portion that extends into Mexico remain unclear (IGRAC 2015). Nevertheless, the pumping patterns shown in Figures 2 and 3 align with the topography on the Mexico side, which supports the geological boundaries proposed by Sanchez et al. (2018a). The pumping area of the Edwards Aquifer extends across different formations on the Mexico side: Austin Fm./Austin Chalk, Presa La Amistad aquifer, Buda-Del Rio Fm./Buda Limestone-Del Rio Clay, Sta. Elena Fm./Sta. Elena Limestone, West Nueces Fm./West Nueces Fm, McKnigh Fm./McKnight Fm., Salmon Peak Fm./Salmon Peak Limestone, Allende-Piedras Negras (Uvalde Gravel), and Kiamichi Fm./Kiamichi Fm. The aquifer areas on the Mexico side correspond mostly to what CONAGUA refers to as the Cerro

Colorado-La Partida, Presa La Amistad, Palestina, Santa Fe del Pino, and Serrania del Burro aquifers, and as mentioned, they disagree with the boundaries identified by Sanchez et al. (2018a). In the case of Austin Fm./Austin Chalk, which performs more as an aquitard in the border region close to Acuna and southeast of Val Verde County, water well depths range from 76 to 366 m, some drawing from this formation but the great majority from the Edwards Aquifer (TWDB 2017). On the Mexico side, a significant number of wells have enough data to confirm water extraction from the Edwards Aquifer at depths from 6 to 673 m (REPDA 2015), and many others suggest similar extraction patterns below the Kiamichi Fm./Kiamichi Fm. and Austin Fm./Austin Chalk (Figure 2). Extraction from alluvial deposits that could be connected to HGUs below the surface (Kiamichi Fm./Kiamichi Fm., Austin Fm./Austin Chalk or Edwards Aquifer) is also significant in this region. Groundwater use is mainly for livestock, agriculture, and urban supply for the municipalities of Nava, Zaragoza, Hidalgo, Jimenez, Guerrero, Muzquiz, and Ocampo on the Mexico side, the Acuna/Del Rio sister cities, and to a lesser extent Allende and the border cities of Piedras Negras/Eagle Pass (Figures 3 and 4). The other outcropping side of the Austin Chalk Fm./Austin Chalk Fm., east of Presa La Amistad Aquifer (Figure 4), shows pumping wells that reach around 100 m down, north of the Uvalde Gravel on the Texas side (TWDB 2017) and under the center and southern part of the Quaternary deposits on the Mexico side which constitute the Allende-Piedras Negras Aquifer. This well pattern of Austin Chalk in this region is considered a modest ETAA. Austin Chalk wells can also be found sporadically in the Edwards Aquifer (Balcones Fault Zone) on the Texas side toward the north, following the same structural trend of the fault zone across Kinney, Uvalde, Medina, and Bexar Counties. See Table 1 for details on the characteristics of ETAAs in this region.

ETAAs in the East Edwards Aquifer Zone

In the case of Presa La Amistad aquifer, around 80% of the water wells on the Texas side draw from the Edwards Aquifer at a depth of approximately 20 m (TWDB 2017). On the Mexico side, all water wells draw from the Quaternary Alluvium at depths between 6 and 30 m (REPDA 2015). Groundwater is used mainly for livestock and domestic needs on the Texas side and for urban use for the cities of Acuna and Jimenez on the Mexico side (REPDA 2015; TWDB 2017). The limited extension of the aquifer does not suggest an ETAA, but notice the higher pumping tendency on the Mexico side.

In the pumping area of the Eagle Ford Fm./Eagle Ford Group (Figure 3), the scattered pattern of well locations in both Mexico and Texas does not suggest an ETAA at the transboundary level. The Upson Fm./Upson Clay (Figure 4) shows a concentration of wells near the center of the Allende-Piedras Negras Aquifer on the Mexico side, and some other wells close to the Rio Grande; however, there are no wells reported within the surficial boundaries of this HGU on the Texas side, and therefore no ETAA is identified. The same condition appears for the San Miguel Fm./San Miguel Fm., Olmos Fm./Olmos Fm., and Midway Fm./Kincaid Fm., which have few reported wells in their corresponding formations on the two sides of the border. There are a few wells in the extreme south of the Midway Fm./Kincaid Fm. on the Mexico side (Figure 4), but they seem more related to the Quaternary region in this area than to the Kincaid Fm./Kincaid Fm. The fact that these formations are not considered to have good aquifer potential might also be a factor in the absence of pumping wells in this area (Sanchez et al. 2018a). The Escondido Fm./Escondido Fm. reports wells close to the Rio Grande at 30 to 50 m depths on the Mexico side, used mostly for livestock in the Guerrero municipality (Grupo Modelo 2003; Lesser-Illades et al. 2008; REPDA 2015). The concentration of wells on the Mexico side of the Escondido Fm./Escondido Fm. and of the Olmos Fm./Olmos Fm. does not provide elements to identify an ETAA within these HGUs. The Allende-Piedras Negras aquifer reports an important cluster of wells along and across the Rio Grande in the sister cities of Eagle Pass and Piedras Negras with a higher concentration of wells on the Mexico side (see Table 1). The identified ETAA in this region is mostly located on the Mexico side where the urban centers of Piedras Negras, Allende, and Guerrero are highly dependent on groundwater for agriculture and urban supply (Sanchez et al. 2018a). Groundwater in this aquifer is extracted at shallow depths of 3–45 m.

ETAAs Gulf Coast Zone

Figure 5 shows the continuation of the HGUs toward the east, with their corresponding pumping patterns, topography (elevation), and the most important rivers. In this region, interesting pumping patterns and therefore ETAAs were identified. First, according to well log information, the confined region of the Carrizo-Wilcox Aquifer pumping area extends to the east below the Bigford Fm./Bigford Fm, El Pico Clay Fm./El Pico Clay Fm., Palma Real-Guayabal Fm./Laredo Fm., and Yegua-Jackson aquifer, with higher well density in the northern parts of these HGUs, mostly in Zavala, Dimmit, and La Salle

Counties, with well depths varying from 12 to 560 m (TWDB 2017). Another pumping pattern is observed close to the border, with a smaller number of wells in the Carrizo-Wilcox aquifer on the Texas side that range from 60 to 90 m and are used for domestic and livestock supply (TWDB 2017). On the Mexico side, the wells of the Carrizo-Wilcox Aquifer are in an area around 60 km south of the border, with depths mostly from 30 to 45 m, though some are close to 100 m (Lesser-Illades et al. 2008; REPDA 2015). The rest of the formation, towards the south on the Mexico side, does not report well productivity and water is mainly used for urban supply for the Hidalgo and Guerrero municipalities (REPDA 2015). The same pattern of low productivity is shown for the Bigford Fm./Bigford Fm. in the southernmost portion on the Mexico side, with shallow wells up to 60 m deep, but a higher density of wells closer to the border (REPDA 2015). There are a few scattered wells reported for the Bigford Fm./Bigford Fm., on the Texas side, concentrated in the northern part of Dimmit and Zavala Counties. ETAAs can be easily seen, based on the pumping patterns of the Carrizo-Wilcox Aquifer between southern Dimmitt County and the city of Anahuac on the Mexico side. In the Bigford Fm./Bigford Fm., well productivity seems to be concentrated on the Mexico side, around 40 km south of the border, with a modest ETAAs area close to the border and some wells on the Texas side (Figures 4 and 5). Table 1 shows the geological characteristics as well as details of the ETAAs in this region.

The depths of water wells recorded for the Palma Real-Guayabal Fm./Laredo Fm. range from 3 to 830 m; they are used mostly for domestic, livestock, public supply, and some irrigation (REPDA 2015; TWDB 2017). An ETAA in this formation can be identified between northern Webb County and the municipality of Mier on the Mexico side. There is another dense pumping area in the northern part of the formation, where there are also a significant number of wells pumping from the Carrizo-Wilcox aquifer.

The pumping patterns of the Yegua-Jackson Aquifer show the greatest depths in the region (between 0 and 411 m) and are mostly located in the southern border region. On the Mexico side, well depths range from 50 to 100 m around the city of Miguel Aleman (REPDA 2015). Considering the pumping patterns and topography of the Yegua-Jackson Aquifer, there is an ETAA close to the border, between southern Zapata County and the municipality of Gustavo Diaz Ordaz on the Mexico side (Figure 5). There is another area of productivity in the northern part of the formation close to the surficial boundary of the Palma Real-Guayabal Fm./Laredo Fm. Groundwater in this area is used mostly for livestock on both sides of the border.

The upper part of the Catahoula Confining System is considered part of the Gulf Coast Aquifer, and it is divided geologically and topographically between the Upper and Lower Catahoula Formation. For this analysis, only the Lower Catahoula Formation is considered (Figure 5). Given the well density, there is an ETAA between northern Starr County and the city of Camargo on the Mexico side, with the highest density close to the river. There are also many wells close to the river, mostly drawing from the Quaternary Alluvium at depths between 30 to 50 m and primarily used for livestock (REPDA 2015; TWDB 2017).

The area over the Gulf Coast Aquifer on both sides of the border encompasses the binationally recognized BRB Transboundary Aquifer. Considering the pumping patterns, the topography on both sides of the border, and the official aquifer boundaries recognized in International Groundwater Resources Assessment Centre (IGRAC)'s inventory, there is an ETAA between the northern limits of Hidalgo County, the western limits of Willacy and Cameron Counties, and the southern limits of the municipalities of Rio Bravo and Matamoros on the Mexico side (Figure 5). Even though the boundaries of the ETAA seem similar to those given in IGRAC's inventory there is a larger area of the aquifer on both sides of the border that should be included because on the Mexico side, the Quaternary portion of the aquifer extends beyond IGRAC's (2015) reported limits. There is a clear concentration of wells close to the border on both sides. On the Mexico side, the most productive region is referred to as the Reynosa-Matamoros aquifer and the Sur de Reynosa Aquifer (CONAGUA 2015d). The highest pumping volumes are concentrated in the alluvial region close to the river, at depths from 10 to 100 m (REPDA 2015). On the Texas side, the region covered by the Beaumont Formation also shows a concentration of pumping at depths from 30 to 110 m (TWDB 2017). Groundwater in this area is mainly used for irrigation and to a lesser extent urban, domestic and industrial supply (TWDB 2017). The border cities of Reynosa, Matamoros, and others rely on groundwater for domestic supply, and some is also used for irrigation on the Mexico side (REPDA 2015). See Table 1 for the compilation of data regarding the identified ETAAs.

DISCUSSION

Implications for Groundwater Management

The approach of this study could have important implications for groundwater management both at domestic and transboundary level worth mentioning. First, this approach redefines an alternative boundary of the aquifer, prioritizing one area over another, focusing on a smaller region (*hot spot*). Therefore, the rest of the area of the HGU as well as the corresponding stakeholders and involved water institutions, are not subject to the management or planning process of groundwater. This fact can facilitate the negotiation process at transboundary, and even at domestic level, as there is less land and water rights associated with the hot spot area. Second, the ETAAs are located within the geological boundaries of the aquifer, regardless of administrative (Mexico criteria) or institutional barriers (e.g., Groundwater Conservation District boundaries in Texas), therefore considering only the local and/or regional authorities actually related to that specific aquifer region. The current administrative boundaries use to manage groundwater resources both in Texas and in Mexico, do not represent the true physical delineation of the aquifers, therefore the ETAAs provide a smaller area of shared land within the actual physical boundaries of the HGUs and where groundwater flows are prioritized over aquifer boundaries. This alternative could potentially reduce tensions among stakeholders, as there is a recognition of a zooning area where groundwater productivity occurs, as well as a different level of priority within the physical limits of the aquifer that deserve a specific level of attention at a local or regional scale, rather than an aquifer-wide scale. Local approaches seem to be gaining attention: they have proven to be more efficient at smaller scales and cooperation efforts more achievable in the short-term (Sanchez and Eckstein 2019).

Third, the pumping patterns reflect the productive areas of the aquifer. Considering the limited data and research on the border region, particularly on the Mexico side, the ETAA approach provides a very efficient way to perform initial groundwater assessments and to identify the location of the hot spots without the need of advanced numerical models, which require significant amount of data that might not be available, as well as time. The ETAAs can be considered as a "first sight" evaluation of any aquifer pumping conditions for initial groundwater management assessments. This initial and simple exercise can reduce controversy related to disparities on criteria used to define aquifer boundaries, as well as reducing the amount of stakeholders involved within the boundaries of the proposed ETAAs.

Finally, this approach has the advantage to be applicable both at a very local level (city level), regional level (district level) or even at binational level (between countries). Therefore, the groundwater management process can integrate as few or as many stakeholders as necessary depending on the scale and the scope (e.g., type of water use) under analysis. Current institutional water regimes governing Mexico and Texas groundwater management could consider using this approach at the scale of *COTAS* (Technical Councils for Groundwater Management, Mexico) or GDCs (Texas). These are the closest models (small-local management scale) that could potentially fit the ETAAs proposed prioritization scheme considering their local institutional jurisdiction over a specific aquifer area.

Limitations of the Approach and Future Research

This approach provides a "first sight" of the hot spots that can be considered a priority area within the boundaries of the HGU. However, the recharge and discharge zones of the aquifer are negligible under the scope and scale of the approach. This fact could discourage its use if the aquifer is under stress or overexploited and its effectiveness on the overall systemic impact of the aquifer might not be significant in the long-term. One possible way to address this limitation for future research is to divide the complete aquifer area into priority zones, where the first priority would be the ETAAs, the second priority of management would be the recharge zones, and so on. This could offer a more holistic approach of the aquifer area and at the same time, the zonification of aquifer areas into priority areas in order to decentralize and compartmentalize the different natural and anthropogenic processes that interrelated with the condition of the aquifer. Although this might be an ideal model, it would require additional data from both sides of the border that might be limited or nonexistent.

Another interesting variable that could be integrated into this approach is pumping rates to estimate groundwater flows and potential cones of depression (if any). However, data on pumping rates are highly variable depending on the HGU. It is also limited in most cases, but could be worthwhile exploring as a next step to finalize the prioritization process of ETAAs. Likewise, considering that there are some HGUs with water quality data, this variable can also add significance to the prioritization process within and between the different HGUs. This is an important variable very likely to be included in future research to narrow down those areas of good quality water and their correlation with the pumping patterns of each ETAA.

Lastly, this approach has the disadvantage that can only be used if pumping patterns are clearly identified. An example is the Edwards Aquifer, where its large extension does not make ETAASs a reliable assessment method.

FINAL REMARKS

Based on the above results, there is the potential to highlight and prioritize some aquifer areas over others within the geological extension of some HGUs. Well density, pumping patterns, topography, geology, and lithological data determine the priority *hot spots* or ETAAs within the surficial and vertical boundaries of the HGUs. A more refined, practical and effective aquifer area can be delineated based on these criteria, offering a more comprehensive and local approach for governance and management options, not just at the binational scale but also domestically. However, as this study shows, not all HGUs offer this possibility. In many cases, the limited number of reported wells or the natural geological features do not allow for alternative options. For example, the hydrogeology of West Texas, which is characterized by bolsons, diversity, and complexity of geological features, and a limited density of wells, does not suggest alternative ETAAs, or prioritization of areas within the geological extension of HGUs that are different from their natural geological boundaries. The Edwards Aquifer has an extensive geological area across Texas and Mexico, with significant well density on both sides of the border. However, the pumping patterns are so varied and uncertain on the Mexico side, and topography so different from one side of the border to the other, that any attempt to delineate an ETAA might leave out important pumping areas on the Texas side or assume too much on the Mexico side.

On the other hand, the Austin Fm./Austin Chalk shows an interesting intermittent pumping pattern that extends across the border toward the Edwards-Balcones Fault Zone, and a high density of wells in the central region of the Allende-Piedras Negras Aquifer. The modest density of wells across the border, between southern Kinney County and the city of Jimenez in Mexico, shows a modest ETAA and hence a potential priority area. The Allende-Piedras Negras Aquifer also shows an interesting ETAA with a concentration of wells on the Mexico side close to the Rio Grande and at the center of the aquifer, but also extending into Val Verde County on the Texas side.

The rest of the HGUs in this region show well density concentrated on *either* the Mexico side (Upson Fm/Upson Clay, Escondido Fm/Escondido Fm, Olmos Fm/Olmos Fm, San Miguel Fm/San Miguel Fm, and Presa La Amistad Aquifers) *or* the Texas side (El Pico Clay Fm/El Pico Clay Fm), implying effective aquifer areas limited to one side of the border (not transboundary). Other HGUs, such as the Eagle Ford Fm./Eagle Ford Group, show scattered and sporadic pumping density areas, making ETAAs unlikely as well.

The region with the most potential for the application of this approach is the Gulf Coast zone, where there is a variety of potential ETAAs. The well density and pumping patterns of the Carrizo-Wilcox Aquifer across the border offer a good example of an ETAA that is distinct from the large transboundary extension of the formation. The same logic applies to the ETAAs of the Palma Real-Guayabal Fm./Laredo Fm., Bigford Fm./Bigford Fm., Yegua-Jackson Aquifer, the Lower Catahoula Confining System, and the Gulf Coast Aquifer. All of them show alternative ETAA delimitations that can be prioritized and assessed at a more regional and local scale. Some pumping patterns at domestic level were also observed at the northern limits of the Carrizo-Wilcox Aquifer, Palma Real-Guayabal Fm./Laredo Fm., and Yegua-Jackson Aquifer, which do not *seem* to have a significant continuous connection with the southern part of the formations.

The ETAA approach is an alternative way to assess priority areas within the natural boundaries of each HGU. Instead of trying to assess aquifers across their complete geological extension, which sometimes results in serious institutional constraints considering the amount of stakeholders and groundwater authorities and jurisdictions involved (e.g., the BRB/Gulf Coast Aquifer), the ETAA aims for a more focused assessment with a regional approach, where applicable governance structures can address groundwater management in a more local, practical and, hopefully, less contentious way.

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