Permanent Forum of Binational Waters

PILOT PROGRAM FOR Knowledge, Development, and Management of SHARED AQUIFERS

Deliverable 1.6

Synthesis report on water supply and demand. Knowledge of the physical conditions of groundwater and aquifers in the study area

Allende - Piedras Negras Transboundary

Aquifer Project

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EXECUTIVE SUMMARY: MAYOR FINDINGS AND KEY RECOMMENDATIONS

This synthesis report presents a **diagnosis** of the current situation of water resources at three scales: local (100km), intermediate (250km) and regional (500km). It provides **recommendations** to augment the **knowledge of water supply and demand** within a binational context. The results of this research may contribute to formulating a sustainable management plan for the water resources of the area under study.

The municipalities with the highest groundwater **demand** at the intermediate scale are Nava and Zaragoza tapping the APN aquifer and Múzquiz the Región Carbonífera aquifer, with withdrawals >100 Mm^3 of groundwater per year (2020). However, given the geography and hydrogeological settings, there is **no competition** between the two municipalities. An attempt was made to compare groundwater use and users on each side of the Mexico/US border at the **local scale**. We found clear and striking differences in the volumes and types of **uses** for groundwater. On the American side, total groundwater use was 8.3 Mm^3/y (2020); whereas on the Mexican side, total groundwater use was 165 Mm^3/y (2020). Groundwater on the American side is supplied by deeper sedimentary aquifers hosted by Cenozoic and Cretaceous rocks; on the Mexican side all withdrawals are from the quaternary uppermost-layer of the APN aquifer, with the exception of some wells, which extract groundwater from a deeper limestone Cretaceous aquifer. **Thus, there is no obvious direct competition for groundwater in aquifers straddling the border. However, a knowledge gap remains in the potential hydraulic connection between the deeper layers across the border.** Agriculture's groundwater use dominates on both sides of the border with 60% on the Mexican side and 72% on the American side. There is no industrial groundwater use on the American side at the local scale, but it can be high at the intermediate and regional scales.

The **dependence** on groundwater is clearly marked in the agriculture sector on both sides, albeit relatively smaller volumes on the U.S side. Surface water supplies most other users on the U.S side and mainly public use on the Mexican side at the local and intermediate scales. This research did not completely cover the regional scale.

One of the main **gaps** in data and information that emerged from this research is the level of hydraulic interaction between the Río Bravo/Grande and the aquifers located along and on each side of the border. Filling in this important gap will require characterization of the geological rift believed to be followed by the river bed and alluvium of the APN border belt, through geological surveys, geophysical exploration and exploratory wells, and analysis of hydrometric records of the river and tributaries. Other actions include: (1) characterize the local groundwater flow system feeding the springs and the artesian conditions of the wells;

(2) update the APN hydrogeological study; (3) evaluate the potential of deep aquifers; and (4) verify if the recharge of the "Maverick" aquifer (US side) comes from the Serranía del Burro (Mexican side). These tasks could be accomplished with follow-up studies using structural geology, remote sensing, isotope analyses, hydrogeochemistry, and monitoring.

The most relevant findings of this research with respect to water dependency in the region are:

- The main water demand on the shallow aquifers in both countries is agricultural use, which is largely predominant, followed by industrial and urban public use.
- At the local scale, the APN aquifer supplies the most significant water demand on the Mexico side. Its shallow and deep units are managed jointly, since the recharge of the former comes largely from the springs generated by the discharge of the latter. The natural variability of rainfall and the imprecise measurement of spring discharge and water withdrawals did not allow to assert if in the long term this aquifer is subject to overexploitation.
- The shallow units of the aquifers in Mexico are considered transboundary in the sense that they present hydraulic continuity across the border. However, the probability that the Rio Bravo/Grande behaves as a hydraulic boundary and the fact that on the U.S side these units are a minor source, it is reasonable to conclude that these units can be managed relatively independently by both countries, without the risk of generating transboundary hydrogeological effects.
- Due to their regional extension, hydrogeological characteristics and extensive outcrop in the mountainous areas with the highest rainfall, it is presumed that the deeper units of the aquifers in question can offer large volumes of groundwater in a sustainable manner, the magnitude of which could not be determined with the information available (a primary estimate was done in this research, bound to be refined, confirmed or refused).
- The available information suggests that the deep units of the aquifers have hydraulic continuity across the border, and that their main recharge zones are located in the Serranía del Burro. Based on this research, it is presumed that it is very unlikely that in the short or medium terms, transboundary hydrogeological effects can be generated.
- Growth in water demand is expected, derived from demographic growth, given the strategic location of the Piedras Negras area, which encourages the expansion of industrial development. Under the current administrative and legal conditions, there would be no availability of water concessions to satisfy new demands, unless new studies demonstrate the existence of greater availability of water and/or a sustainable management plan is implemented.

- Inclusive and adapted sustainable plans driven by socially-responsible environmental strategies based on data-driven decisions seems to be the strategy moving forward as water scarcity due to climate and demands drive water consumption at a local and regional scales.

The above findings emphasize the need to increase groundwater knowledge in the study area in order to prepare quantitative sustainable management plans, and, if possible, at the binational scale. To the questions on whether there is water scarcity, poor governance, lack of knowledge, or ill-informed decisions, the findings suggest that there is enough water for all users, but not enough knowledge of the groundwater resources, which prevent taking informed decisions on water management in a shared governance context.

A better understanding of the existing water sources (pools and fluxes, surface water and groundwater), the main users, and the water use in a binational context, provides a **global overview** of water sustainability in the study area.

It is recognized that agreeing on shared management plans with groundwater users and other stakeholders is usually difficult, so the recommended approach is to take one action at a time within a regional framework. The knowledge acquired, the strategies proposed, and a group of stakeholders, will be a first step into a potential regional alliance to ensure that the water management units (rivers, springs and aquifers) maintain or recover a sustainable condition. Progress could be slow, but it will be based on informed decisions.

I. Introduction and objectives

This report represents preliminary results of current collaborative Allende-Piedras Negras Transboundary Aquifer project (APN-TBA project) of the Permanent Forum of Binational Waters (PFBW). It is a comprehensive report providing analysis with recommendations identifying the current state of the water resources of the area.

This is a synthesis report on water supply and demand, with an integrated knowledge of groundwater and the aquifers located in the study area, as well as the main water users and water use on both sides of the border. It is based on results generated from deliverables D1.2 and D1.3. The report remains focused and dynamic, including conceptual schematic ideas and figures never published before; these are based on existing knowledge and expert opinion. Important knowledge gaps are provided, which will help guide future research work in the region.

The approach used is comprehensive, focused on groundwater and aquifers as they relate with other components of the hydrological cycle, as well as with the environmental, socio-economic and legal conditions of the study area. Likewise, cross-border aspects and expected changes in the supply and demand of water resources are analyzed, derived from demographic growth, economic development trends and the effects of exploitation of those resources.

Thus, the main objectives of this deliverable are to:

- Formulate a diagnosis of the current situation of water resources in three scales of the study area;
- Provide recommendations to enrich the knowledge of water supply and demand within a binational context;
- Define risks and opportunities in water-related issues; and
- Contribute to formulate a sustainable management plan for the water resources of the area under study.

II. Area under study

The study area includes the border portion of the Río Bravo/Grande basin that extends in the states of Texas, on the U.S side, and the state of Coahuila, on the Mexican side. The study considers three geographic scales, the "Regional scale", the "Intermediate scale" and the "Local scale". These are depicted in Figure 6.1 and explained below.

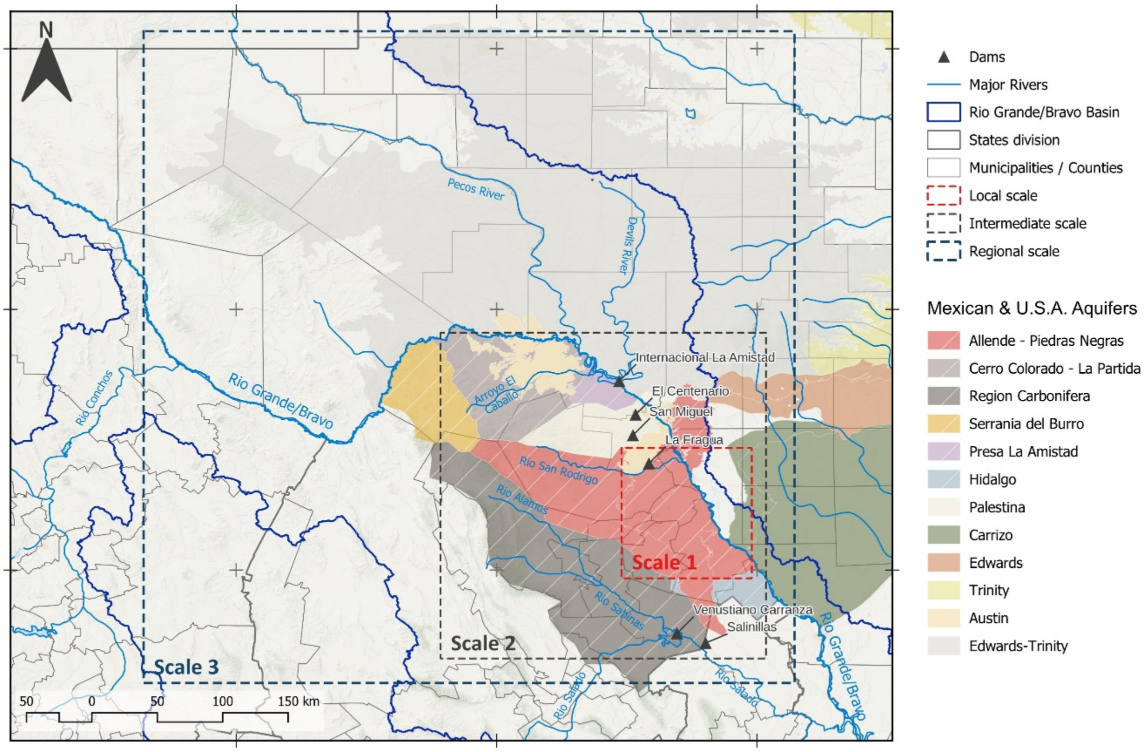

Figure 6.1. Study area with three scales.

In this report, as for others in this project, we focus on the water resources in the entire *water system*, encompassing three scales as indicated in Figure 6.1: local, intermediate and regional. These scales are crucial in understanding the role of groundwater flow, from recharge to discharge areas, in solving water management and environmental problems. As defined in Deliverable 1.2 of this project, data and information includes the three scales considering water inflows and outflows and uses of land. The region under study, was divided into nested watersheds and nested aquifers intended to evaluate surface water and groundwater fluxes and pools and how these may influence water decisions in a shared management environment. Further, we understand the system to be *transboundary*, given recent research showing water interactions among the APN and the Maverick aquifers (Rodriguez et al., 2020; TWDB, 2021).

The water bodies located within the three scales are listed below.

Scale 1
The **local** scale includes:

Groundwater: the APN, Karst-Ki aquifer and Maverick aquifer.
Surface water: Rio San Rodrigo and la Fragua dam on the Mexican side, and La Amistad dam on both sides.

Scale 2

The **intermediate** scale includes:

- Groundwater: APN, Karst-Ki, Serrania del Burro, Palestina, Hidalgo and Carbonifera aquifers on the Mexican side. As well as the Maverick aquifer, and parts of the Edwards and Carrizo aquifers on the American side.
- Surface water:
  - Rivers: El Caballo, San Rodrigo, Almos and Sabinas on the Mexican side. Pecos and Devils on the American side.
  - Dams: La Amistad Centenario, San Miguel, La Fragua Venustiano Carranza y Salinillas on the Mexican side; and La Amistad on the American side.

Scale 3

The **regional /basin** scale:

- Groundwater:
  - Aquifers on this scale are unidentified on the Mexican side; Edwards-Trinity on the American side.
- Surface water:
  - Parts of Rio Conchos and Rio Salado on the Mexican side; and Pecos and Devils on the American side.

2.1 Conceptual two-dimensional groundwater flow

Figure 6.2 shows a NW-SE or W-E cross-section, which depicts schematically the groundwater flow systems (GWFS), springs, and artesian wells in the study area. The 2D sketch was designed based on current knowledge acquired in deliverable D1.2 and the field trip of November/December 2023 by members of the PFBW. The study area is characterized by four geographically and topographically well-defined zones: Sierras, foothills, foreland and plains, as shown in Figure 6.2. These four zones, plus the structural geology of the area, define aquifers and groundwater movement in the region; basically, three aquifer formations: a quaternary Fm (Qc), an upper cretaceous Fm (Ks), and a lower cretaceous Fm (Ki). Recharge, springs, artesian pressure, and three general groundwater flow systems (GWFS) complete the groundwater framework in the study area's local and intermediate scales.

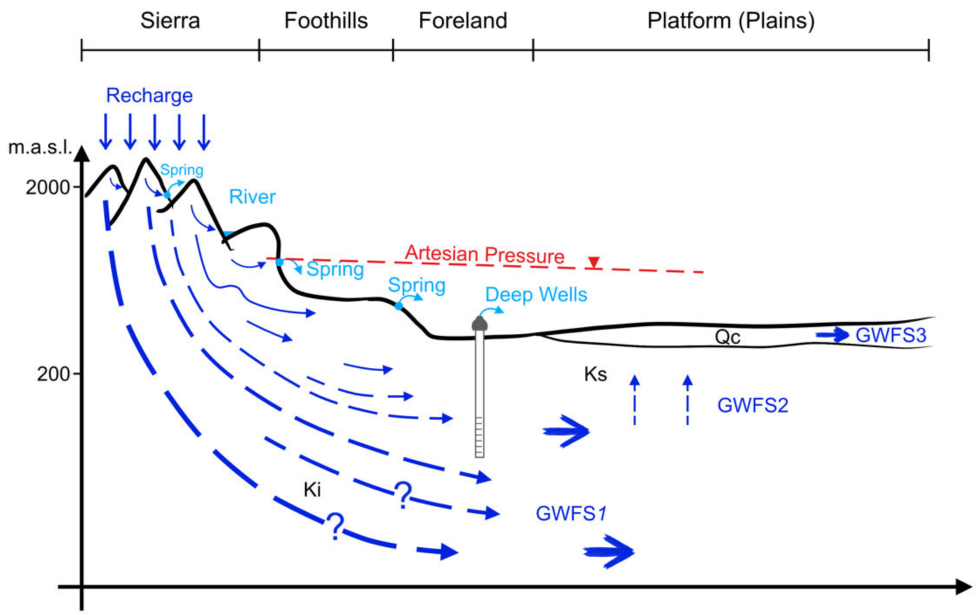

Figure 6.2. Springs, artesian wells, and groundwater flow systems (GWFS) in the APN-Maverick W-E region.

III. Synthesis of previous studies

This section integrates and synthesizes the information and results derived from the activities corresponding to deliverables D1.2, D1.3, which are presented in detail in the respective reports. The first and second sections describe the general knowledge of the aquifers considered in the APN-TBA project at the regional and intermediate scales. The third section, analyzes a broader description of the "Allende-Piedras Negras" aquifer at the **local scale, as it is the one with the greatest aquifer potential** and the most important for the purposes of this work.

3.1. Regional scale

In the region included by the APN-TBA project, the main sources of water are the aquifers widely described in D1.2, the Rio Bravo/Grande and its tributaries. **The runoff of the Rio Grande, controlled in international dams, is regulated and distributed between both countries in accordance with the provisions of the 1944 Water Treaty.** The allocations of the Rio Grande runoff that correspond to Mexico and the United States are shown graphically in Figure 6.3.

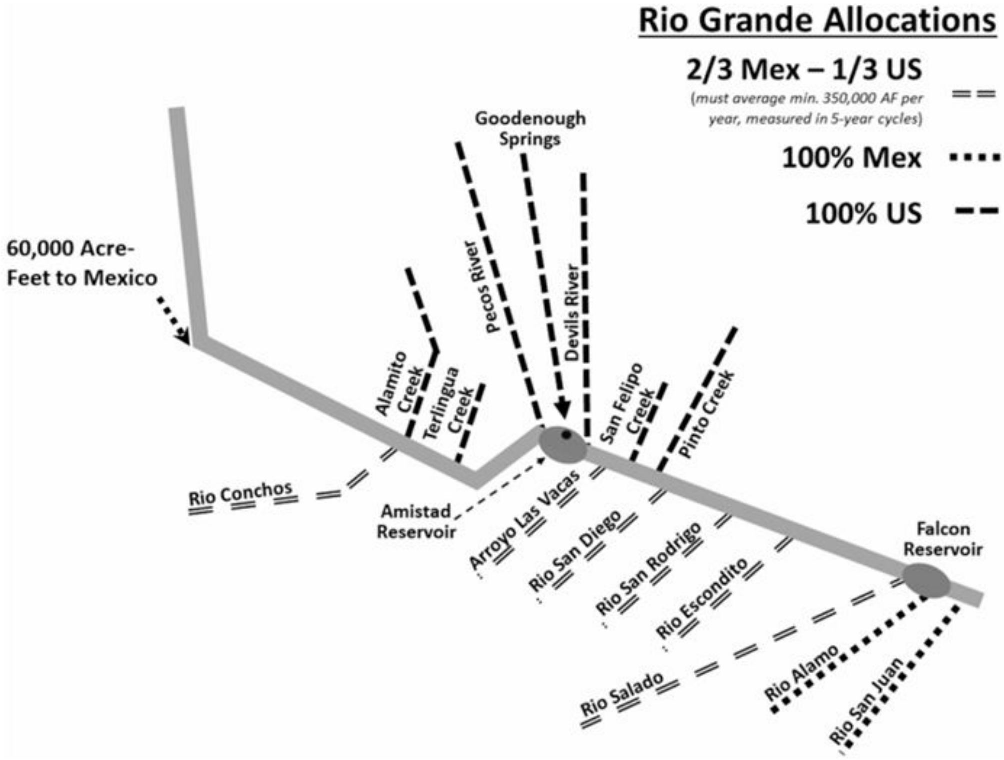

Figure 6.3. Rio Bravo/Grande Allocations according to the 1944 Treaty. Source: Buono and Eckstein (2022).

In the region covered by the APN aquifer, the Rio Grande receives water from its tributaries on its southern bank that contributes significant volumes during rainy years, and the underground contribution coming from the shallow unit of the APN aquifer. **It is unknown if the river also receives water contributions from the deeper unit of the aquifer.** Apart from a concession granted to the CFE (Federal Electricity Commission, Mexico) to divert 46.5 Mm^3/y of water from the river for industrial use, there are no other concessions to divert water from the river in the section that underlines the APN aquifer; **However, there appears to be incidental exchange of water between the river and aquifers** depending on their water levels (gradient).

As far as aquifers are concerned, at this scale and in general, the stratigraphic column is essentially the same in both countries, although there are some differences in the name and geographical delimitation of their geological formations. There is relative continuity or stratigraphic similarity from one country to the other; but, with the information available, the **underground hydraulic continuity across the international border is doubtful because the hydrogeological role played by the Río Bravo/Grande is not clear:** in some sections of its right bank, outcrops of groundwater ("lloraderos" or weep holes) are observed, which can be the discharge of marginal storage generated during river floods and/or the discharge of shallow units; while in other canyon-type sections large "sinks" of water are observed in its channel. Therefore, though there seems to be geological continuity across the border, the actual shallow groundwater flow from one side to the other seems to be driven by the hydraulic energy of the Rio Grande's flow.

3.2. Intermediate scale

In general, the stratigraphic column and conceptual models of the Mexican portions of the aquifers considered in the APN-TBA project are similar. For all the six aquifers in the Mexican side at the intermediate scale, two main aquifer units can be differentiated: a shallow one made up of unconsolidated materials and conglomerates, and another deeper one made up of carbonate rocks from the Lower Cretaceous.

3.2.1. Upper aquifer units

These units extend under valleys and plains (Qc, as shown in Figure 6.2). Their thickness varies in the area in the range of a few tens of meters, and they are limited underneath by low permeability formations. In the Mexican side, the shallow units of the aquifers "Allende-Piedras Negras", Región Carbonífera", "Serranía del Burro", "Palestina", "Santa Fé del Pino", "Cerro Colorado La Partida", "Presa La Amistad" and "Hidalgo" **are accessible to all sectors due to their wide distribution in under the valleys in the plains, where the water table is shallow.**

As a whole, the average natural recharge of the shallow units of the aquifers listed in the previous paragraph is of the order of 656 Mm^3/y, as shown in Table 6.1. **More than 85% is concentrated in the shallow units of the "Allende-Piedras Negras" (APN) and "Región Carbonífera" (RC) aquifers,** which partly are fed by the infiltration of the water discharged by the numerous springs that emerge on the flanks of the Sierra del Burro and Lomerío de Peyotes. Natural recharge varies from year to year depending on the rainfall regime, in which "dry" cycles of several years alternate with rainy cycles of two to three years.

The natural discharge of the shallow units in the Mexican side takes place in the channels of rivers and streams, which are intermittent with the exception of the rivers and streams that drain the shallow units of the aquifers APN y RC**. Under natural conditions, all of them discharged into rivers and streams tributaries of the Rio Grande, and/or underground into the river itself. The non-tributary shallow unit (RC), discharges to the Sabinas River whose runoff is stored in the Venustiano Carranza Dam**, located in the southeastern portion of that aquifer intended for agricultural use. Another part of the natural discharge from shallow units occurs by evapotranspiration in areas with shallow water tables.

Table 6.1. Technical administrative condition of the aquifers of the Mexican side of the APN aquifer at the intermediate scale (CONAGUA/DOF, 2023).

	Volumes in Mm^3/y							
Aquifer	**R**	**DNC**	**VCAS**	**VEALA**	**VAPTYR**	**VAPRH**	**VEXT**	**DAS**
Allende-Piedras Negras	496.5	274.3	156.6	80.4	4.4	0.2	241.5	**-19.4**
Cerro Colorado - La Partida	9.6	0	0.7	0.4	0	0	1.1	8.5
Región Carbonífera	84.1	39.1	36.5	35.7	0.0	0.1	72.3	**-27.3**
Palestina	10.3	4.6	2.0	1.3	0	0.1	3.4	2.3
Hidalgo	3.6	0	1.9	1.8	0.1	0	3.8	**-0.2**
Santa Fe Del Pino	19.5	1	0.2	1.6	0	0	1.8	16.7
Presa La Amistad	20.2	10.7	1.5	0.8	0	0.1	2.3	7.1
Serranía Del Burro	11.9	0.3	0.7	0.2	0	0	0.9	10.7
Total	655.7						327.1	**-46.9** 45.4

R: Recharge; DNC: Compromised Natural Discharge; VCAS: concessioned/allocated volume of groundwater; VEALA: volume of water extraction in the areas of provisional suspension of free draw up water and those registered in the Permanent National Registry; VAPTYR: volume of water extraction pending titling and/or registration in the REPDA; VAPRH: volume of water corresponding to reserves, regulations and water programming; DAS: Groundwater availability; VEXT: Total Extraction Volume.

The shallow units of the aquifers are independent of each other on the Mexican side. With the information available, **it cannot be defined if these units are fully transboundary** (see Deliverable D1.2 for geologic maps**),** in other words, there is doubt of the hydraulic connection with their respective U.S sections, because Tertiary and Cretaceous formations outcrop in the border belt, reducing the length and thickness of the permeable sections.

According to data officially published by CONAGUA in November 2023 (DOF, 2023), **the total volume of water concessions allocated from the shallow units of the aquifers at the intermediate scale was 327 Mm^3/y.** From this volume, 88% corresponds only to the APN and RC aquifers, where most of the population and development is concentrated. Of the total volume, about 200 Mm^3/y were concessions allocated before the declaration of suspension of "*libre alumbramiento*" (free exploitation) of April 2023. The remaining volume, about 127 Mm^3/y, corresponds to extractions approved in the registration process of pending water concessions that took place afterwards, which have not been physically verified. Actual extractions vary from year to year depending on rainfall which, in turn, determines the discharge of the springs. Likewise, there are concessions that are not used continuously every year, extractions that exceed the amount concessioned, or those that are not reported or are clandestine.

At this intermediate scale, about 60% of the volume of water extracted from shallow units is used for agriculture, 24.8% for industrial use, 12.5% for multiple uses, 1.7% for urban public uses in cities and smaller towns, another percent corresponds to domestic, livestock and service uses. **Actual extraction for agricultural purposes varies with the availability of surface water (springs and streams), logically, it is higher during "dry" years.** Extraction for industrial use increased with the rise of mining activity in the period 1990-2015, only to decline over the course of the last decade (Lesser, 2014).

3.2.2 Deep aquifer units

These units outcrop in the Serranía del Burro, in the Lomerío de Peyotes, and in the other mountain ranges that limit the shallow units; in the valleys and plains they underlie the Upper Cretaceous rocks (karstified lower Cretaceous formation shown schematically as "Ki" in Figure 6.2). In general, their hydraulic conductivity is high and is reflected in the flow of the springs generated by their discharge on the flanks of the mountain ranges, as well as in the wells built in the Serranía del Burro, with flows of 54 to 280 liters per second of water and salinity less than 300 ppm.

The recharge of these deeper units takes place due to the infiltration of rain and runoff on their outcrops. Part of its natural discharge takes place through springs, such as those that spring up on the flanks of the Serrania del Burro and Lomerío de Peyotes (shown schematically in Figure 6.2); **it is assumed that most of the discharge occurs at greater depths under the control of the geological structure, towards lower elevation discharge areas probably located outside the APN, both in Mexico and the United States** (e.g., the Maverick basin; TWDB, 2021).

In other mountains of the region considered in the study (e.g., Lomerío de Peyotes, Anacacho mountains), there are extensive outcrops of the same aquifer formations in both countries; but, **at the regional and intermediate scales, there is not enough information available to estimate their aquifer potential (renewable volume) and infer the characteristics of the regional groundwater flow**. However, the geological surveys and satellite images provided a better characterization of the stratigraphy and the major features of structural geology -large faults and fractures, the probable "rift" of the Rio Grande and major folding- which allows to assume the existence of one or more deep groundwater flow systems that extend to both countries.

These deeper aquifer formations emerge on mountain flanks, on land far away from the wells located on the Plains and made up of heterogeneous rocks of great hardness and very variable permeability in the area, so their exploitation is usually expensive and unsecured. This implies that they could only be accessible to priority sectors (urban, public) and those with greater economic capacity (industrial). It can be stated that these deeper formations constitute the main sources of water, due to the large extension of their recharge-receiving outcrops, located in the rainiest portions of the region.

At this scale on the U.S side, the Carrizo-Wilcox Aquifer is a large prolific Aquifer hosted by fluvial to deltaic formations of Cenozoic age of the Upper Gulf Coast system and running from Louisiana to the Mexico-US border. It has a large confined section dipping to the Gulf Coast and a narrow outcropping band. The Carrizo-Wilcox Aquifer offers a variety of facies from coarse to fine grained sands, sometimes massive (Carrizo Sands) loosely with some interbedded siltstones and shales. Recharge occurs primarily through exposure of the Carrizo-Wilcox sands to precipitation at the outcrop and where the outcrop is incised by creeks or streams. In the border region, it reaches a thickness >500 m and yields moderate to large quantities of groundwater, but the yield decreases with distance from the outcrop.

The other very extensive aquifer at this scale, extending to the regional scale, is the Edwards Aquifer, which is a world-class intensively-karsted aquifer developed in south-central Texas on carbonates of Cretaceous age. Intersection of the Edwards Formation present on the broad Edwards Plateau to the north and west of Kinney County with the Balcones Fault Zone created the flow conduits characteristic of the very productive aquifer. The Balcones Fault zone is a series of large normal faults marking the transition from the Plateau to the Gulf Coastal Plain. In its westernmost occurrences (Kinney County), the two along-strike bands that typically form the Aquifer are approximately 20 km wide. The band to the north represents the recharge zone through karstic features and river beds, whereas the confined section to the south represents the main body of the Aquifer. The fresh water-holding section is about 200 m thick there and the natural egress of the water is several large springs.

3.3. Local scale, the APN aquifer

The area in which this aquifer extends is the one with the greatest development and population density, and the one with the greatest water supply of those users considered in the APN-TBA project, mostly due to the abundant springs discharged by the deep aquifer unit on the bordering mountain flanks.

In the valley, the phreatic levels of the shallow aquifer range at depths between 3 and 30 m, with increasing values from the Río Grande towards the flanks of the mountain. Groundwater flows from these flanks towards the Rio Grande; locally, the water flows into the piezometric depressions generated by the concentration of pumping from industrial wells. These depressions were greatest during the time when the mining company MICARE lowered water levels to exploit the coal deposit underlying the shallow aquifer unit; when this activity declined, the water table recovered, forming a large lake in the mining pit called Tajo III, whose closure has been deferred to date. **During dry periods (years and/or seasons) the aquifer generates the base flow of the rivers, tributaries of the Rio Bravo/Grande, while in rainy years they feed the shallow unit of this aquifer.**

Currently, **there is a clear gradient of groundwater flow towards the Rio Bravo/Grande, which apparently receives the discharge from the shallow unit throughout the border section.** However, low permeable rocks that underlie this unit and emerge discontinuously on some parts along the river, seem to be limiting the underground discharge to the permeable sections carved by the tributary currents of the river. **It is estimated that the discharge from the shallow unit to the river is of the order of 25 Mm^3/y** (Lesser, 2014). **It remains to be defined if the river functions as a drain that receives the discharge of the aquifer from both countries, or if there is underground flow from one to the other,** with flow directions depending on the intensity of the pumping on each side of the border. In any case, it is not likely that this transboundary groundwater circulation, or the exchange of the aquifer with the river, is of significant magnitude with respect to the magnitude of the other terms of the balance of each portion of the aquifer (e.g., runoff).

The Serrania del Burro is the main recharge area for the deep aquifer units, its discharge originates the Nava springs and its pressure is manifested in the artesian wells drilled in the city of Zaragoza. Most of the overflowing volume, from 4 to 8 m^3/s, which varies seasonally and annually with the magnitude and distribution of rainfall, is collected through canals and distributed for the irrigation of agricultural lands, where infiltration in canals and the return of irrigation surpluses feed the shallow aquifer unit. This is captured through several hundred wells and shallow wells scattered in the valley, which extract a volume of water between 150 and 240 Mm^3/y, depending on the flow discharged by the springs, a volume of which 70% is used for agriculture, and the rest for domestic, livestock, urban public and industrial uses.

The potential of the deep aquifers is unknown, but it is presumed that discharge from the springs only corresponds to the upper portion of those units, and that at greater depth a greater fraction of the recharge circulates to **other discharge areas located on the other slopes of the Sierra del Burro, probably outside the limits of the APN aquifer and even into the U.S side of the border, as suspected in the Maverick Basin** (TWDB, 2021), which would make it transboundary. **The connection between the Rio Grande and deep aquifers is also unknown.**

The deep and shallow aquifer units of the APN aquifer do not have direct hydraulic connection (although there may be some connection through leakage of the upper Cretaceus unit, Ks in figure 6.2); **but the recharge of the shallow one depends largely on the discharge of the deeper one. Thus, although the extraction of the deep aquifer does not compete directly with that of the shallow one, the increase in the discharge of the deep aquifer (Ki in Figure 6.2) through pumping wells or artesian wells could reduce the flow of the springs**, with the consequent impact on the users. In this sense, there is competition between the two, which requires them to be managed jointly. **However, since the lower unit is very thick, it is possible that wells that capture it at greater depths will not affect the local flow that feeds the springs.**

3.4. Groundwater use

Groundwater is critical for the development of many activities along the Mexican/U.S border. Data obtained from concession volumes from the REPDA on the Mexican side, and from the estimated volumes of water extraction by the TWDB on the U.S side, reveal that **agriculture**

predominates as the largest user of groundwater in most of the municipalities and counties surrounding the APN aquifer. However, industrial and urban public uses represent high water withdrawals in municipalities and counties near the border, such as Nava, Zaragoza, Maverick, Webb, and Val Verde (Figure 6.4).

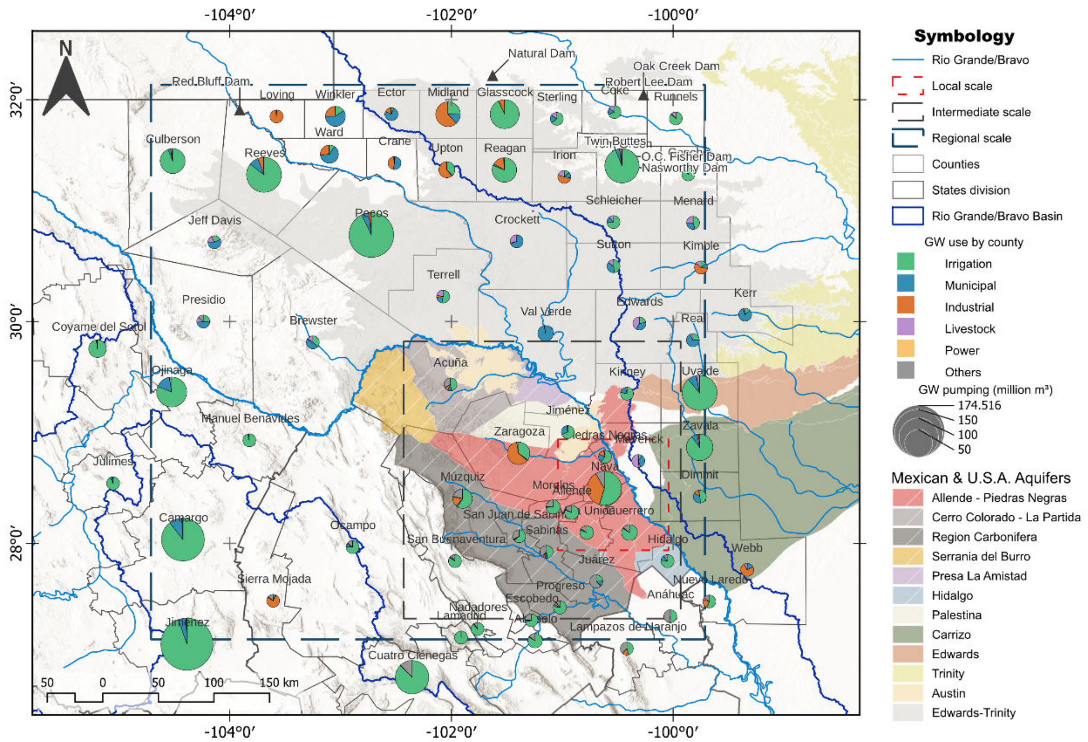

Figure 6.4. Groundwater use at the county scale for the year 2020. Data from Mexico was obtained from the REPDA dataset for 2020 and from the estimations of the Texas Water Development Board for 2020.

The municipalities with the highest demand for groundwater within the limits of the intermediate scale of analysis are **Nava and Zaragoza in the APN aquifer and Múzquiz in the Región Carbonífera aquifer**, with withdrawals higher than 100 Mm^3 of groundwater per year, according to 2020 records.

At the intermediate scale of analysis, **the APN and RC aquifers stand out with the highest demand for groundwater, exceeding 165 and 43 Mm^3 for 2020** (Table 6.2), **and 241 and 72 Mm^3 for 2023** (Table 6.1), respectively. This data underscores the critical importance of these aquifers. The accumulated groundwater extractions for 2020 in the rest of the aquifers in Table 6.2 do not exceed 4 Mm^3 and are even below the volume of groundwater for industrial use in the RC aquifer.

Table 6.2. Annual groundwater concessions volume (Mm^3/y) for aquifers in the Mexico side at the intermediate scale. Data from Mexico was obtained from the REPDA data set for 2020.

Aquifer	Agriculture	Multiple Uses	Domestic	Industrial	Livestock	Public supply	Services	Total
Allende - Piedras Negras	98.3912	15.0414	0.0610	47.6147	0.1794	1.4441	1.8441	164.5758
Cerro Colorado - La Partida	0.1620	0.5680	0.0000	0.0000	0.0136	0.0669	0.0000	0.8105
Región Carbonífera	25.6904	10.6713	0.0202	4.6179	0.4143	1.5375	0.0127	42.9643
Palestina	0.4536	0.0793	0.0000	0.0000	0.0126	0.5164	0.0000	1.0619
Hidalgo	0.3480	0.0330	0.0000	0.0000	0.0000	0.0531	0.0000	0.4341
Presa La Amistad	0.8895	0.0637	0.0000	0.1861	0.0005	0.0549	0.0050	1.1996
Serranía del Burro	0.0000	0.0000	0.0000	0.0000	0.0000	0.0485	0.0000	0.0485
Totals	**125.890**	**26,440**	**0.081**	**52.40**	**0.614**	**3.690**	**1.852**	**210.97**

For the purpose of this report, an attempt was made to compare groundwater use and users on each side of the border at the local scale (APN aquifer). Figures 6.5 schematically present those numbers for the year 2023 for the Mexican side, and Figure 6.6 for 2020 for the U.S side. There are clear and striking differences in the volumes and type of use of groundwater on each side of the border, as well as in the units where the water comes from. Groundwater use volumes on the US side are reported by county boundaries; the numbers shown in Figure 6.6 are for Maverick and Kinney counties, which draw water from the Carrizo-Wilcox aquifer and primarily the Edwards-Trinity aquifer, respectively. While on the Mexican side the values of Figure 6.5 are shown for users located within the limits of the APN aquifer, where all extractions are from the upper quaternary (Qc), with the exception a fraction of the industrial use of groundwater.

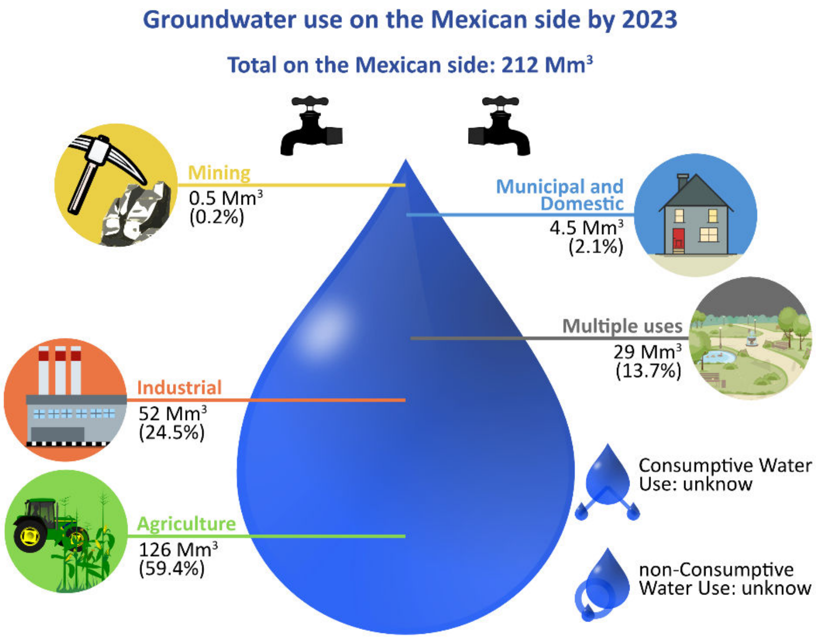

Figure 6.5. Groundwater use on the Mexican side at the local scale (APN aquifer). Values are from the DOF published in 2023.

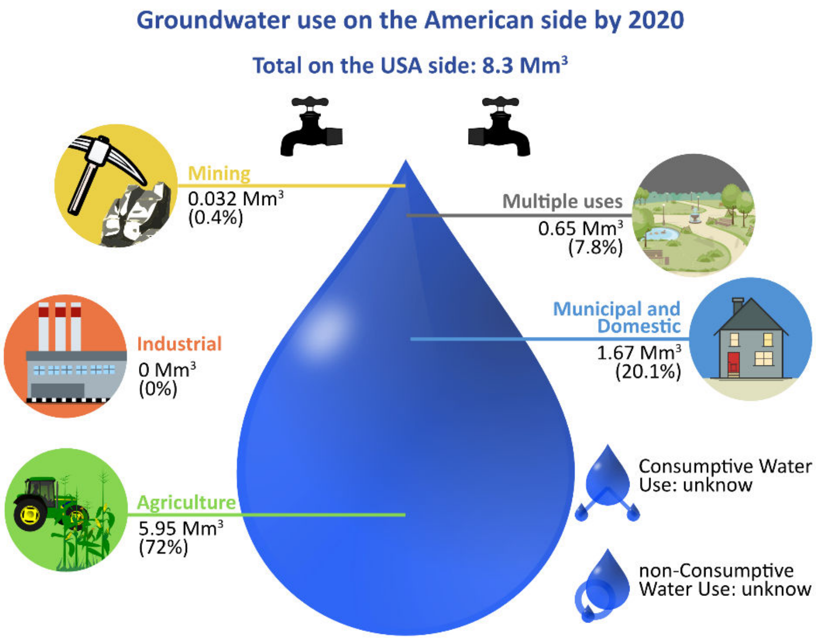

Figure 6.6. Groundwater use on the American side at the local scale. Values from the TWDB dataset for 2020.

The extraction of water from the shallow units on the U.S. side represents less than 4% of that corresponding to the Mexican side, which is mainly due to the fact that on the U.S side the Tertiary age rocks predominate in these units, which are not very permeable, and the Qc formation is almost non-existent. **Therefore, a direct competition (demand) for groundwater in the same shallow units on either side of the boundary is not likely.**

The use of groundwater for agriculture dominates on both sides of the border with 60% on the Mexican side and 72% on the U.S side. Industrial use (including livestock) is null at the local scale, but can be higher at the intermediate and regional scales. **On the Mexican side industrial use (includes mining) is equivalent to 25% of the corresponding total extraction.** Multiple uses are a mixture or combination of the main ones.

IV. Water supply and demand

On the Mexican side, the official definition of water supply includes the average recharge of the aquifers, the average runoff of the tributaries of the Rio Bravo/Grande – whose contributions to that river are not committed in the Water Treaty of 1944 – and the volume of wastewater returned by urban and industrial users.

As for the Mexican portion, the most recent data on supply, demand and availability of groundwater officially published by CONAGUA (DOF, 2023) are shown in Table 6.1. As indicated in previous sections, data must be taken with reservations and its corresponding limitations due to the reliability of official data and the limited knowledge on other adjacent aquifers.

As for the U.S side, water demand, supply, and water needs are considered for the Maverick and Kinney counties according to each economic activity. Water uses include municipal, manufacturing or industrial, steam-electric water representing consumption by power plants, mining, (hydraulic fracturing) by the oil and gas industry, irrigation, and livestock and other diffuse water use (county-other). Water supply is either from surface water (rivers, lakes, and reservoirs) or from groundwater, which is extracted from several aquifers.

4.1. Groundwater supply

Annually, the water supply varies due to the irregular rainfall regime, in which cycles of four to seven “dry” years alternate with one or two years of extraordinary rainfall. This variation mainly affects the shallow units of the APN and Region Carbonifera (RC) aquifers at the intermediate scale. At this scale, the groundwater supply of the aquifers considered in the Mexican side is 656 Mm^3/y (average annual recharge of the aquifers), **of which 89% corresponds to the APN (76%) and RC (13%) aquifers,** and 11% to other aquifers.

In particular, the APN's groundwater supply can include volumes of water derived from the Río Bravo/Grande by nearby pumping wells on both sides of the border (induced recharge), to the extent that they do not affect the water commitments established in the respective international treaty. According to the results of Rodriguez et al. (2020) using a numerical flow model, the river is a gaining river in a section of the APN aquifer, and a losing river in another section, which implies that by pumping wells near the border, **additional volumes of groundwater could be made available from the river flow, apparently without causing reductions in groundwater levels in the neighboring country.** If the Rio Bravo/Grande indeed plays that role, it is worth asking whether the shallow unit of the APN should be considered transboundary.

On the U.S side, water supply is either from surface water Rio Bravo/Grande and tributaries, or groundwater extracted for the Carrizo-Wilcox aquifer underlying the Maverick County. Groundwater supply was around 2.5 Mm^3/y in 2020, with expectations to decrease to 1.88 Mm^3/y to 2070. Moreover, surface water supply from the Rio Bravo/Grande to Maverick County is higher than 50 Mm^3/y corresponding mainly to irrigation use. Whereas, the surface water supply from the Rio Bravo/Grande to Kinney County is lower than 4.7 Mm^3/y.

4.2. Groundwater demand

Groundwater demand in the Mexico side is assumed equivalent to the extraction of groundwater, which according to official data is about 327 Mm^3/y (Table 6.1) with the following distribution: 241 (74%) correspond to the APN, 72 (22%) to the RC aquifer, and the remaining 16 (4%) to the other aquifers. **Almost the total water volume is extracted from the shallow units**, noticing that in the two referred aquifers, the discharge ranges from 6 to more than 10 m^3/s through springs. In these two aquifers, about 85% of water extraction is for agricultural and industrial uses, and the rest for urban public, domestic and livestock uses.

In the APN and RC aquifers, water demand changed over the last 20 years, with a natural increasing trend associated with demographic growth and immigration. This growth is associated with industrial development in the Piedras Negras area, increase in agriculture, and a notable increase of mining activity during the period 1990-2010, followed by a decline in the last 10 to 15 years (SGM, 2021). In particular, the main mining company in the Piedras Negras area, MICARE, has suspended most of its production. Consequently, groundwater extraction for this use has decreased in the same proportion.

In the future, it is expected that the demand for water will increase with population growth and the expansion of industry. The population in the municipalities within the APN aquifer extension on the Mexican side increased from 159,657 inhabitants in 1990 to 261,406 inhabitants in 2020, **an increase of 63% compared to 1990** (see Figure 6.7; INEGI, 2020). On the other hand, **water demand** (Figure 6.8) **showed a greater increase than that of the population itself** (Figure 6.7), where the groundwater demand on the Mexican side of the APN almost doubled from 2001 to 2020 (CONAGUA's REPDA data).

The population in Maverick and Kinney counties has increased in similar proportions to municipalities in Mexico, reporting about 39,842 inhabitants in 1990 and 61,481 inhabitants in 2020, representing an increase of 54% compared to 1990 (Figure 6.7). Maverick County population is estimated to grow to 107,327 in 2070, and Kinney county's population is estimated to stay stable at ~3,700 inhabitants by 2070 (TWDB, 2020).

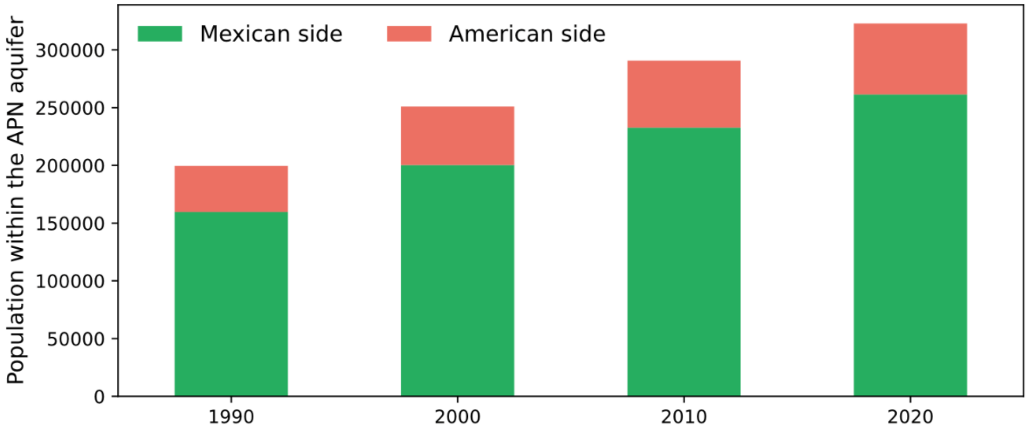

Figure 6.7. Population growth within the APN aquifer in Mexico and USA. Source: own elaboration using data from INEGI and USA Facts.

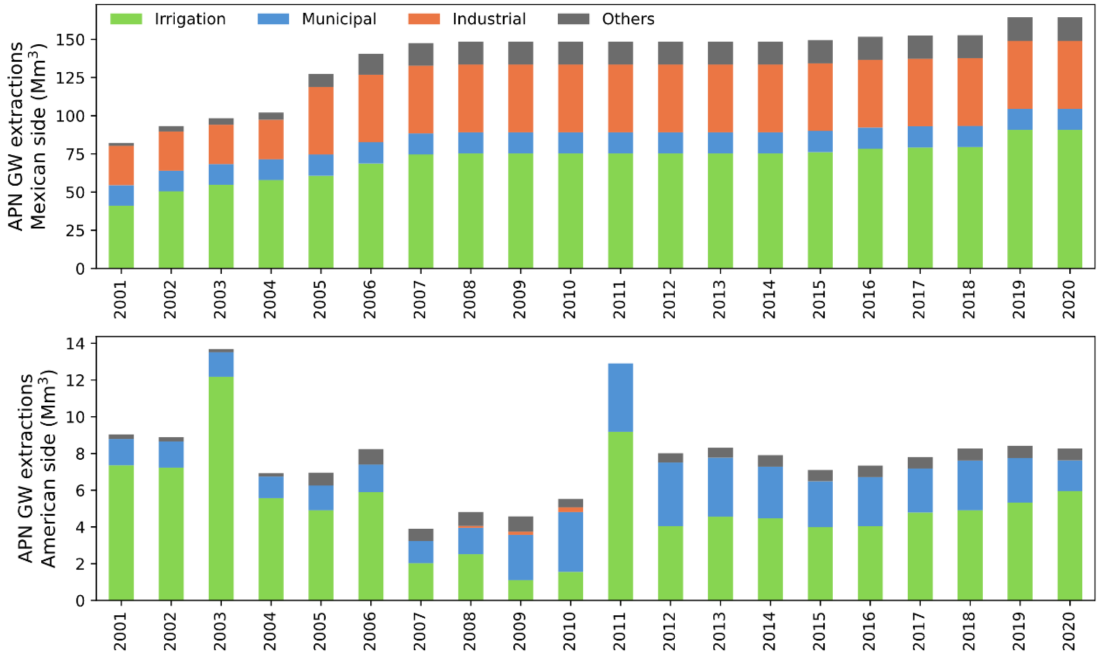

Figure 6.8. Historical GW pumping within the APN aquifer for the Mexican and American sides. Source: own elaboration using data of REPDA from CONAGUA and the TWDB.

The mining sector on the Mexico side, is unlikely to have a significant local resurgence, given that the current federal government intends to carry out a constitutional reform that prohibits the granting of concessions for open pit mining development and for “fracking” (a portion of a binational deposit of “shale gas” extends in the Piedras Negras area). However, this will depend on the public policies that, in terms of water and energy, are implemented in Mexico by the upcoming administration. It is possible that they will decide to undertake the exploitation of these deposits to reduce the current dependence on the United States, at least during a transition towards renewable energy.

The agricultural sector is the most water consuming on both sides, and the least efficient in terms of water use. In general, it will be necessary to take actions to modernize and increase the efficiency of this sector on both sides of the border. In particular, on the Mexican side, the agricultural sector that depends on the APN aquifer (shallow and deep units) deserves special attention, since the advantage of having the water discharged by the springs and being exempt from taxes for the use of water, encourages its less efficient use.

4.3. Groundwater availability

On the Mexican side, the “Availability of groundwater”, “AGW”, is defined in the LAN as: “the average annual volume of groundwater that can be extracted from an aquifer for various uses, in addition to the extraction already concessioned and the committed natural discharge, without endangering the balance of the ecosystems”. This concept determines if it is feasible to allocate new concessions, which are only granted if the “AGW” is positive. **In the case of the APN and “RC” aquifers, their value is negative, which implies that new water concessions cannot be granted for any use** (Table 6.1).

In the case of the APN aquifer, a large part of the discharge from the springs is considered compromised because, in fact, it is being used by farmers and ranchers, it contributes a fraction of the base flow of the streams that are tributaries of the Rio Grande and generates the springs of the border strip, which would have to be preserved if a certain environmental value is recognized. However, it is likely that more reliable data obtained by updating official studies, could modify this situation in a favorable way.

It is very likely that there is greater availability of water in deeper aquifer units, but this would have to be demonstrated through regional and local studies carried out by the competent authorities (CONAGUA) in collaboration with other parties (academia, concessionaires, development banks, industry, NGOs). These studies would have to be validated by CONAGUA in a way that any potential additional availability of groundwater would be legally allocated for new water concessions.

On the U.S side, there is no “official” definition of groundwater availability. When making decisions for groundwater exploitation, the TWDB, the body that regulates water use in the State of Texas, uses a practical approach based on carefully-calibrated numerical models to assess the availability of groundwater. The Groundwater Availability Models (GAMs) simulate the volumes of groundwater that are available using detailed water budget approaches that are applied to Groundwater Management Areas (GMA) that cover specific aquifer regions. Water users in these regions use the model's information on groundwater availability to design their own groundwater withdrawals according to their Desired Future

Conditions (DFCs). **This is a very decentralized approach with the users deciding on their own DFCs and TWDB acting as facilitator to make sure those conditions are met. It is a bottom-up process in which stakeholders play a very important role as planning groups.**

In this approach, the **models are the main living tools updated as data improves; they are constantly calibrated against a monitoring groundwater network, and data is collected and made transparent to the public.**

The 5-county region (Kinney, Maverick, Uvalde, Zavala, and Dimmit counties) host 2 aquifers of regional importance (major aquifers): the Edwards Aquifer in Kinney and Uvalde counties and the Carrizo-Wilcox Aquifers in Maverick, Zavala, and Dimmit counties. As shown in Table 6.3, the 5-county region belongs to two GMAs. GMA 13 includes the Carrizo-Wilcox Aquifer and other clastic overlying minor aquifers that follow the same structural pattern (Maverick, Zavala, and Dimmit counties). GMA 10 consists of the karsted carbonate Edwards Aquifer as it intersects the Balcones Fault zone (Edwards BFZ) (Kinney and Uvalde counties). Both aquifers are very prolific and produce large amounts of water. Stakeholders of each Regional Water Planning Groups decide the so-called Desired Future Conditions, typically an average drawdown over an area, and the Modeled Available Groundwater (MAG) is computed at a 50-year horizon.

Table 6.3. Modeled available groundwater in the USA aquifers summarized by source and county.

		Volumes in Mm^3/y					
Source	**County**	**2020**	**2030**	**2040**	**2050**	**2060**	**2070**
Carrizo-Wilcox	Dimmit	5.093	5.093	5.093	5.093	5.093	5.093
Carrizo-Wilcox	Maverick	2.519	2.519	2.468	2.361	1.937	1.888
Carrizo-Wilcox	Uvalde	3.670	1.518	1.021	1.021	1.021	1.021
Carrizo-Wilcox	Zavala	43.977	43.548	43.383	43.259	42.863	42.796
Edwards BFZ	Kinney	7.797	7.797	7.797	7.797	7.797	7.797
Edwards-Trinity	Kinney	86.764	86.764	86.764	86.764	86.764	86.764
Austin Chalk	Uvalde	3.620	3.620	3.620	3.620	3.620	3.620
Buda Limestone	Uvalde	0.935	0.935	0.935	0.935	0.935	0.935
Edwards BFZ	Uvalde	18.955	18.955	18.955	18.955	18.955	18.955
Edwards-Trinity	Uvalde	2.458	2.458	2.458	2.458	2.458	2.458
Leona Gravel	Uvalde	11.576	11.576	11.576	11.576	11.576	11.576
Trinity	Uvalde	0.981	0.981	0.981	0.981	0.981	0.981

Extracted from GAM Run 17-027 MAG (TWDB, 2017) and 16-026 MAG V.2 (TWDB, 2018)

4.4. Pool and fluxes for surface water and groundwater

The summary of main surface and groundwater fluxes and pools within the Local and Intermediate scales are shown in Figure 6.9 and Figure 6.10. Surface water flows have been estimated from the data provided by the International Boundary and Water Commission (IBWC, or CILA), where the Lower Pecos and Devils rivers contribute with the highest flows to the Rio Bravo/Grande at the intermediate scale of analysis, exceeding 266 and 316 Mm^3/y (8.45 and 10.03 m^3/s), respectively (CILA, 2020). In the APN study area, **the river with the highest flow is the San Diego River, with more than 177 Mm^3/y (5.6 m^3/s), followed by the San Rodrigo River, with more than 127 Mm^3 (4.0 m^3/s)**. Meanwhile, the accumulated streamflow on the Rio Bravo/Grande, below La Amistad dam, is about 1,973 Mm^3/y (62.6 m^3/s).

At the intermediate scale, main recharge areas for the GWFS are located in the Serranía del Burro and the foothills of the APN aquifer. La Amistad Dam is the main pool of water in the study area, with a storage capacity of 1,800 Mm^3. Moreover, main groundwater pools correspond to the Serranía del Burro and the APN aquifer, with about 1,800 and 3,600 Mm^3, respectively (Fig 6.10).

Moreover, flows concerning the GWFS shown in Figure 6.2 and Figure 6.9 have been estimated for this study using Darcy's Law. Horizontal flow discharging to Rio Bravo/Grande corresponding to GWFS-3 was estimated as 29 Mm^3/y from the groundwater levels provided by CONAGUA for the year 2017 and a transmissivity value of about 350 m^2/d reported by Lesser (2012), where these values were interpolated and spatially averaged at groundwater cells. Previous estimates ranged from 23 to 25 Mm^3/y (Lesser, 2012).

Due to the lack of information, knowledge of GWFS-2's fluxes is limited; however, in the case of GWFS-1, a series of assumptions can be made to approximate a range of fluxes. For example, Figure 6.2 shows that the groundwater flow gradient can be determined following the artesian pressure based on the elevation of the recharge zone on the Serrania del Burro relative to the location of the springs at the foothills. Moreover, limestones' hydraulic conductivity has been reported from 0.52 to 22 m/d (Báez and Hernández-Espriú, 2024), and assuming an aquifer thickness similar to the Maverick Basin aquifer of 304.8 m (Fox, 2022) the estimated GWFS-1 fluxes range from 74 to 1,853 Mm^3/y (2.3 to 58.8 m^3/s).

For instance, with a preliminary quantitative analysis using data and information derived in this study**, it was estimated that the deeper Limestone lower cretaceous unit (Ki in Figure 6.2) has a storage capacity between 6 to 600 Mm^3 and a groundwater flow system between 74 to 1,853 Mm^3/**y. **The GWFS-1 is twice as large as the one for the APN (GWFS-3 of 29 Mm^3/y) and could equal the average flow in the Rio Bravo/Grande (average flow of the Rio Bravo/Grande at the San Antonio River junction of 1,976 Mm^3/y).** However, more studies are required to confirm these values and reduce the uncertainty of the estimates shown in this report.

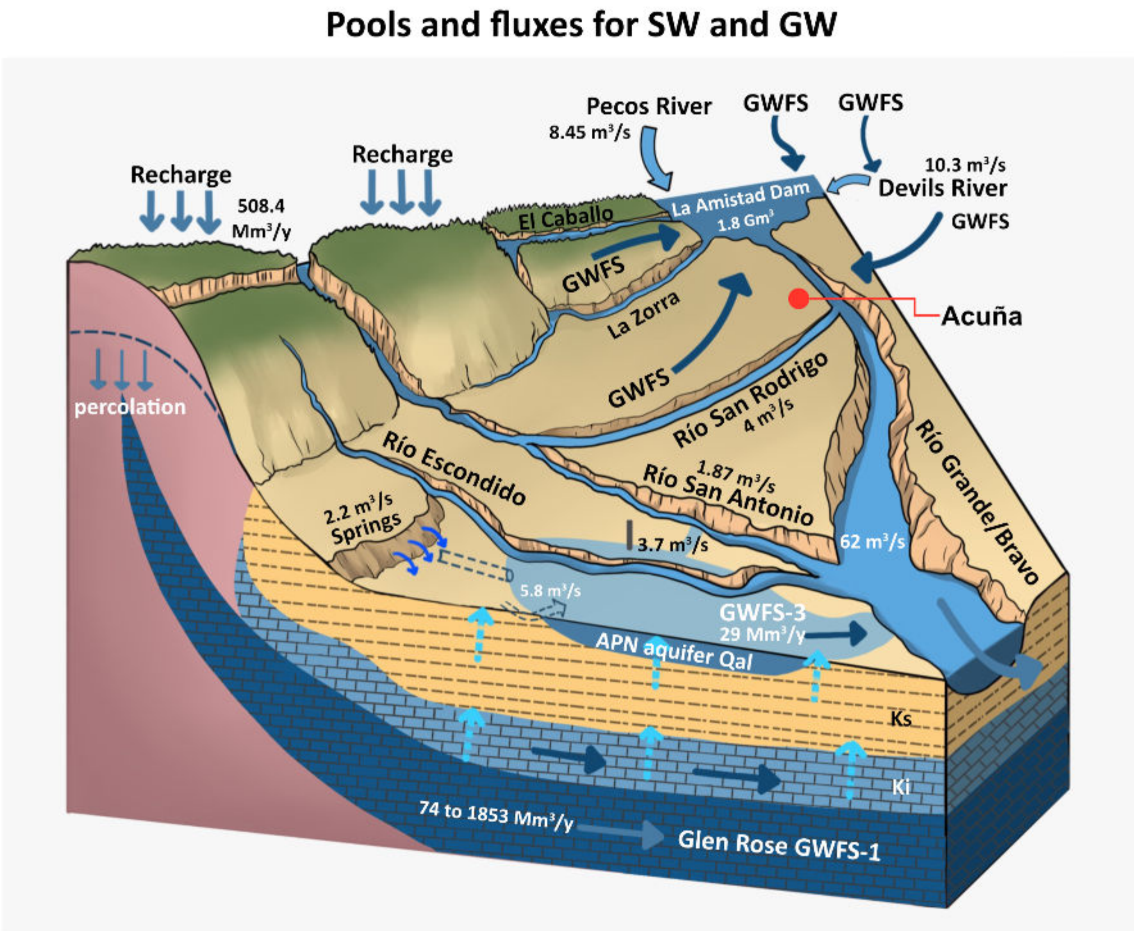

Figure 6.9. Schematic view of pools and fluxes for surface water and groundwater in the APN study area.

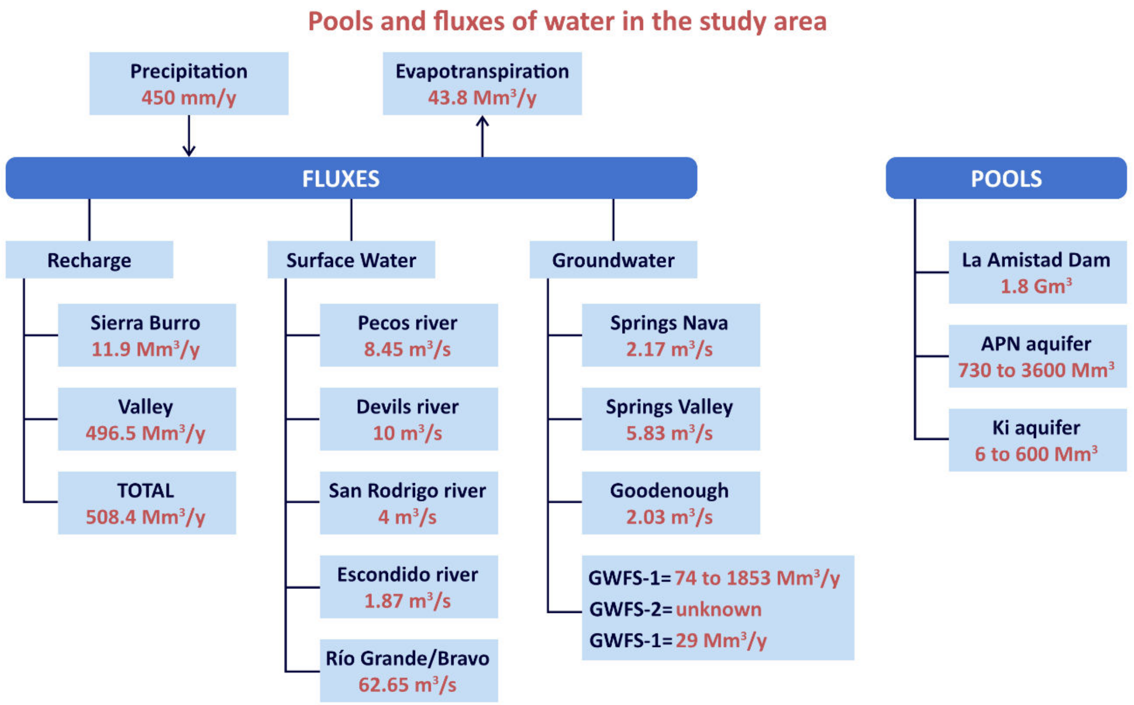

Figure 6.10. Pools and fluxes for surface water and groundwater in the APN study area.

V. Legal and administrative considerations

5.1. The Mexican Legal Framework on Water

"The Mexican Constitution" establishes that groundwater may be freely extracted by the owner of the land, but for reasons of public interest the Government may issue decrees to regulate, prohibit or reserve its use and exploitation. In order to control the granting of water concessions, the "AGW" determines the type of regulation to be applied: if it is positive, a "Regulation" applies, and if it is negative, a "Ban" applies. On April 5, 2013, the Federal Government decreed the provisional suspension of free exploitation (*libre alumbramiento*) throughout the national territory, while the respective regulations were established, the regularization of pre-existing users was carried out and the "AGW" was determined.

In particular, the aquifers considered in this study are within the jurisdiction of the Río Bravo Basin Organization of CONAGUA, based in the city of Monterrey, State of Nuevo León, and the APN aquifer had a COTAS (aquifer management organizations) that apparently stopped operating. On October 31, 2013, the "DECREE *establishing as a regulated area that occupied by the aquifer called Allende-Piedras Negras, located in the State of Coahuila*," was published in the DOF. In the other aquifers, which correspond to less developed areas, studies were initiated to determine their "AGW" and began the process of regularization and registration of pre-existing users. **Up to 2024 this has not been concluded so they do not have the respective regulations.**

In the APN aquifer most of the water is used by agriculture. **The volume used by this sector pumped out of the Sabinas-Reynosa (Qc layer) is licensed and registered in the REPDA. However, the volume of water destined for agriculture that comes from springs, considered as surface water (physically and administratively), is not duly granted.**

VI. Transboundary considerations

The shallow units of the aquifers called "Allende-Piedras Negras", "Palestina", "Presa La Amistad" and "Hidalgo" have lithological continuity with the respective American portions. In their natural state, these aquifers exchanged water with the Rio Bravo/Grande, the direction and magnitude of the flow depend on the relative position of their water levels. Increased groundwater extraction on both sides of the border can induce river flow into aquifers; however, according to the records of the hydrometric stations installed in the section in question, the minimum flow of the river is around 60 m^3/s, so it is not likely that it will be significantly reduced by the extraction of groundwater on both sides of the border. **In this case, the river would be functioning as a hydraulic border that avoids transboundary effects or mitigates them.** According to the results of the hydrodynamic simulation model published by Rodriguez et al. (2020), most of the discharge to the Rio Bravo/Grande now comes from the Mexican portion of the APN aquifer; while pumping wells in United States territory derives more water from the river.

However, the possibility is not ruled out that, depending on the stratigraphy, the lowering of groundwater levels caused by the pumping of wells on one or both sides of the border is sufficient to break the direct connection of the aquifer with the river, giving rise to the underground flow from one country to another below the river's channel. In any case, given the reduced magnitude of the groundwater flow, **it is estimated that the effect of groundwater extraction in one country on the neighbor would not be significant in terms of water volume. If anything, it could have some impact on the shallow catchments closer to the border or on the riparian vegetation. If this is confirmed in subsequent studies, it would have to be decided whether or not the APN aquifer is considered transboundary.**

The interaction of the Río Bravo/Grande with the aquifers is an important aspect to investigate, since the extent to which hydrogeological effects can spread from one country to another across the border depends in part on it. According to information provided by the Mexican Geological Service, the channel of the Rio Bravo/Grande was formed in a large crack in the Earth's crust, of tectonic origin, called the "Río Grande Rift", which depth is unknown and whose course is parallel to the orientation of the faults and folds of the Cretaceous formations. If the crack extends to depths lower than the current river bed, it is likely that it vertically cuts the Cretaceous formations, in which case it could be acting as a hydraulic boundary that partially or totally separates the shallow and deep aquifer units.

In any case, **it can be stated that under current conditions there is no competition between both countries for the use of deep units, although they have hydraulic continuity across the border.** Although its exploitation is important on the U.S side, it is not likely to affect the deep units on the Mexican side, because they are upstream from the piezometric point of view: isotopic analysis seem to demonstrate that the Serrania del Burro is a recharge zone for the Maverick aquifer in the United States.

The "Serrania del Burro" and "Cerro Colorado-La Partida" aquifers are not transboundary, because they are limited to the north by mountain ranges that separate them from the Rio Bravo/Grande. Their shallow units, of reduced extension and thickness, extend at the bottom of small valleys and intermontane plateaus. The "Región Carbonífera" aquifer is not transboundary either, because it extends to the southeast, recognizing the Sabinas River as the main drain, whose runoff is regulated by the "Venustiano Carranza" dam, and used downstream in Irrigation District 004, "Don Martín", located in the State of Nuevo León.

VII. Sustainable management plans

In Mexico, due to the dry climate that prevails in much of its territory, groundwater is vital for the development of all sectors. In the middle of the last century, the creation of some 80 irrigation districts and several hundred irrigation units took place in the arid portions of the country, which led to the construction of thousands of wells. At that time, the study of aquifers was in its infancy, so its sustainable potential was not yet known; this fact, the need to increase the agricultural frontier and the deficient control of groundwater extraction, led to the generation of numerous cases of overexploitation with severe impact on the environment.

In the last 20 years, some actions have been developed to address this situation through the implementation of sustainable management plans, but plans are still not prioritized at different levels of authority, funding has been limited, and stakeholders' participation is still sporadic. Ideally, sustainable management plans should include strategies such as: **demand management (efficient use, reuse, recirculation, etc.), changes in the use of water and soil, conjunctive use of groundwater and surface water, legal regulation of water and water management. desalination of brackish or salt groundwater, modernization and irrigation technology, rainwater harvesting and artificial recharge (MAR),** among others.

Water management is based on the Principle of Sustainability, considering water as a heritage resource that must be preserved, in quantity and quality, for the harmonious development of all sectors (including the environment) of present and future generations. To achieve this goal, management plans are yet to be developed aimed at ensuring that the management units (river basins and aquifers) maintain or recover a sustainable condition. In most cases social participation has been somehow active, but in practice the implementation of the plans has been unsuccessful due to a lack of political and social will to apply their provisions, especially when they involve changes in uses and restrictive measures.

In relation to the area of study, the APN aquifer requires the implementation of a management plan due to its greater development and growth potential. At a conceptual level, the management plan that is proposed to be formulated for this aquifer could include actions to reduce water consumption and increase its supply, some of which are listed below with brief descriptions.

- **Domestic and livestock use**

Divert water from the channels or streams that carry the water discharged from the springs, to ensure the supply of good quality water to the rural population and livestock facilities.

Improve the physical conditions of the rural population's groundwater collections (dug wells and shallow wells).

- **Urban public use**

Consider the feasibility of delivering water from the artesian wells to complement the supply of cities and larger towns.

- **Agricultural use**

Promote the modernization of irrigation to increase its efficiency and reduce its consumption; and formalize the legal and administrative situation of farmers who receive runoff irrigation.

- **Environmental use**

The competent authorities would have to decide whether Tajo III should be closed, in accordance with the provisions of the concession granted to the mining company, or if the provision is modified to leave it open, depending on the benefits and harms that may entail. On the one hand, it has been used for aquaculture and recreational purposes on a small scale and probably has a certain local beneficial effect on the microclimate. On the other hand, the open pit is a body in which a significant amount of water is lost through evaporation of groundwater, and such activities could generate organic matter and potentially contaminate solid waste.

- **Generation of electrical energy for public service**

Investigate the possibility that CFE uses water from Tajo III for the processes of its coal-fired plant, recirculating the water through pipes and serpentine tubes, in order to liberate its water concession for 29 Mm^3/y of groundwater, previously defining whether that pit remains open or closes as established in the water concession granted to the mining company.

- **Industrial use**

Increase the use of wastewater in activities that do not require drinking water. Reuse wastewater for internal services and processes. It could be reused outside, in other related companies or in other activities, which could reduce the extraction of water from the shallow aquifer.

- **Social participation**

The formulation and implementation of this plan necessarily requires the coordinated participation of all sectors -users, authorities, society, academia, etc.- in a socialization process. In these processes, CONAGUA has had the participation of Basin Councils and COTAS. In previous administrations, these organizations participated in the preparation of the regulations for the APN aquifer. However, during the current administration its implementation lost continuity and the respective COTAS were dissolved. It is, however, possible that some members who continue to reside in the locality may participate or provide information to facilitate their reintegration (see more on this topic in Deliverable 1.5).

VIII. Gaps on data and information

This section lists the main "gaps" that have been identified in the analysis of the information obtained and proposed actions to cover these in subsequent stages of the APN-TBA study in order to achieve its final objectives.

8.1. Definition of the hydraulic interaction of the Río Bravo/Grande with the aquifers

The occurrence and magnitude of transboundary effects depends in part on this interaction. To better define it, it is proposed:

- Characterization of the rift that defines the river bed and the subsoil of the APN border belt, through geological surveys, geophysical exploration and exploratory wells;
- Analysis of the hydrometric records of the river and its tributaries, to estimate the volume of water it exchanges with the subsoil;
- Define the hydraulic connection of the shallow unit with the American portion of it, to conclude if it could be considered transboundary.

8.2. Characterization of the local flow system that generates the springs and the artesian wells

It is required to define whether there is a possibility of wells hydraulically interfering with springs and, if applicable, to reduce or prevent this effect. Actions proposed:

- Monitor and perform complementary hydrogeochemical, piezometric and isotopic analysis of artesian water;
- Seasonal and annual correlation of rainfall and spring discharge;
- Analysis of spring flow decay curves;
- Interference testing between wells and springs.

8.3. Measure the vertical distribution of the piezometric load and characteristics of the water in the Serranía del Burro

It is important to evaluate the possibility of capturing lower strata of the deep unit, without affecting the wells or the discharge of the springs. Actions proposed:

- Interference testing between the wells supplying good quality water and the deeper exploratory well that captured brackish and sulphated water;
- Geophysical explorations (TEM's) in the catchment area of wells.

8.4. Update of the APN hydrogeological study

In previous studies, water balances of the APN aquifer have been proposed considering time intervals in which the recharge and extraction conditions have been different due to natural causes (fluctuations in rainfall) and/or anthropic causes (changes in actual extractions and/or in the volumes granted according to the REPDA). Actions proposed:

- Determine the current volume of groundwater extraction;
- Apply remote sensing technology, which allows knowing the current irrigation surface and its variation over time, and specific software to determine the consumption of crops and natural vegetation;
- Analyze infiltration in the channels and its contribution to the recharge of the shallow aquifer;
- Study the discharge of the shallow aquifer due to evaporation in the lake of Tajo III and in areas with shallow water table; and
- Diagnose the situation of water supply to rural populations, in terms of hydraulic infrastructure, quantity and quality of water.

8.5. Evaluation of the potential of deep aquifers

Due to their regional extension and hydraulic characteristics, it is presumed that the deep aquifers (mainly, Lower Cretaceous formations) are the source of water with the greatest potential, of which until now only their natural discharges (springs) are used. However, its sustainable potential has not been quantified and it is unknown whether it is a large binational aquifer or independent aquifer blocks separated by faults and folds. To cover this "gap" it is required:

- More detailed recognition of the geological structure through remote sensing and terrestrial geological surveys;
- Monitor and analyze the piezometric, hydrogeochemical, isotopic and topographic water discharged from wells and springs.
- Verify if the recharge of the "Maverick" aquifer comes from the Serrania del Burro.

8.6. Preparation of binational sustainable management plans

In this research, conceptual guidelines are proposed for the development of the sustainable management plan for the APN aquifer. In a subsequent stage, the formulation of an executive project of that plan will be required, where objectives, actions, goals, participants, execution times, financing and monitoring are clearly stated. Some of these items are suggested in deliverables 1.4 and 1.5.

IX. Conclusions

From the integration and analysis of the information collected and analyzed in this research, the following main conclusions emerge.

1. In the region covered in this study, Mexico and the United States have water resources contained in rivers, aquifers and other water bodies. The main source of surface water

is the Río Bravo/Grande, whose runoff is distributed between both countries in accordance with the provisions of the 1944 Water Treaty. Groundwater resources are contained in the shallow and deep units of the aquifers defined for the purposes of this work. **At the regional scale, these sources offer sufficient volumes of water to maintain current developments.**

2. **At the regional scale, the shallow aquifer units of greatest extent and potential are located in the Mexico-side of the APN aquifer.** They are accessible for all uses, and according to the most recent official data, the water supply - equivalent to their average annual recharge - is estimated at 656 Mm^3/y, which is concentrated in the "Allende-Piedras Negras" and "Región Carbonífera" aquifers. **In the United States, shallow units are of much less relative importance, due to their reduced extension and low permeability; their water supply is unknown.**
3. The water demand of the shallow units on the Mexican side - equivalent to their concessioned volume - was 327 Mm^3/y in 2023, concentrated in the two aforementioned aquifers. **For 2020, groundwater demand within the APN aquifer in the Mexican side was about 165 Mm^3/y, and about 9 Mm^3/y for the American side.** In both countries, agricultural use is predominant, followed by industrial and urban public use.
4. At the local scale, the "Allende-Piedras Negras" aquifer supplies the most significant water demand on the Mexico side. Its shallow and deep units are managed jointly, since the recharge of the former comes largely from the springs generated by the discharge of the latter. According to the most recent official data, its concessioned volume of water is greater than the renewable volume, therefore it does not have water availability to grant new concessions. However, **the natural variability of rainfall and the imprecise measurement of spring discharge - one of its main sources of recharge - and water withdrawals did not allow to assert if in the long term this aquifer is subject to overexploitation.**
5. **The shallow units of the aquifers, in Mexico named "Allende-Piedras Negras", "Palestina", "Presa La Amistad" and "Hidalgo", are considered transboundary in the sense that they present hydraulic continuity across the border, although the underground flow sections along it are narrow and thin** due to the outcrop of poorly permeable Cretaceous rocks. Considering this condition, the probability that the Rio Bravo/Grande behaves as a hydraulic boundary and the fact that on the American side these units are a minor source, it is reasonable to conclude that these units **can be managed with relative independently by both countries, without the risk of generating transboundary hydrogeological effects.**
6. Due to their regional extension, hydrogeological characteristics and extensive outcrop in the mountainous areas with the highest rainfall, **it is presumed that the deep units of the aquifers in question can offer large volumes of groundwater in a sustainable manner, the magnitude of which could not be determined with the information available (a primary estimate was done in this research, bound to be refined, confirmed or refused).** However, due to their special distribution and/or depth, in Mexico they would not be accessible to sectors with lower economic capacity.
7. The available information suggests that **the springs from the "Allende-Piedras Negras" and "Región Carbonífera" aquifers correspond to the discharge of local**

flow systems from the respective deep units, and that **at greater depths there are regional flow system that discharges on the other slopes of the Serrania del Burro and Lomerío de Peyotes, and even in the American side of the border.**

8. **The available information suggests that the deep units of the aquifers have hydraulic continuity across the border,** and that their main recharge zones are located in the Serrania del Burro. Likewise, due to the reduced extraction of the deep unit on the Mexican side, and since that side corresponds to the upstream portion of the regional flow system that make up these units, **it is presumed that it is very unlikely that in the short or medium term, transboundary hydrogeological effects can be generated.**
9. Growth in water demand is expected, derived from demographic growth and the strategic location of the Piedras Negras area, which encourages the expansion of industrial development. **Under the current administrative and legal conditions, there would be no availability of water concessions to satisfy new demands,** unless new studies demonstrate the existence of greater availability of water and/or a sustainable management plan is implemented.
10. **In the short or medium terms, it is likely that the negative impact of climate change on water resources will cause a reduction in the availability of surface and groundwater,** the mitigation of which should be contemplated by budding a numerical model and simulating the behavior of water sources in different supply/demand scenarios.
11. **Inclusive and adapted sustainable plans driven by socially-responsible environmental strategies based on data-driven decisions** seems to be the strategy moving forward as water scarcity due to climate and demands drive water consumption at a local and regional scales.

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