Allende-Piedras Negras Transboundary Aquifer Project

Extensive technical report with main data, gaps, and research needs

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Deliverable 1.2
Annex A

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1. DATA AND INFORMATION OUTLINE

This report is part of the Allende-Piedras Negras Transboundary Aquifer (APN-TBA) Pilot Project, a project of the Permanent Forum of Binational Waters (PFBW). This collaboration is intended to provide scientifically-based knowledge on transboundary aquifers and watersheds, and transboundary groundwater and surface water using a holistic approach on the assessment and management of transboundary aquifers toward their sustainable development.

The objective of this report is to integrate existing data and information from previous geological, hydrogeological, geochemical, and environmental studies of the APN-TBA, in order to develop an integrated dataset for study of the full aquifer system. This report represents annexe A of deliverable 1.2, it should be consulted together with the two other annexes, B and C. The three annexes constitute a comprehensive review of previous and current data, information, and a variety of studies of the APN-TBA on both sides of the Mexico/US border. These have been compiled, analyzed, and are synthesized in this report; thus, this deliverable represents a synthesis of knowledge on the aquifer as per 2024.

For the purposes of this project, three main spatial scales of analysis have been defined: Local Scale, corresponding to an extension of 100 km and overlapping the APN aquifer; Intermediate Scale, with an extension of 250 km and covering the aquifers APN, Región Carbonifera, Serranía del Burro, Cerro Colorado – La Partida, Palestina, and Hidalgo, all of them in the Mexican side; and the Regional Scale, with an extension of 500 km including the aquifers of the Intermediate Scale and the Edwards – Trinity, and Carrizo, in Texas.

To understand the conceptual hydrogeological models and the connections between scales, data corresponding to geology, hydrogeology, groundwater, surface water, hydro-geochemestry, and the environment was collected from technical reports, scientific publications, and databases from Mexico and the USA. Furthermore, this report aims to describe what is known related to the dynamics of groundwater flow systems, what is missing, and what type of research is needed to fill in the gaps.

All aquifers have information in most sections, but this varies according to their socioeconomic importance. Still, more information related to hydrological, geophysical studies, geological wells-logs, and hydrogeochemical records is needed. This lack of information leads to the absence of conceptual and numerical models for aquifers on the Mexican-side under study. In addition, there is a lack of information on the interactions of groundwater flows between Mexico and the United States, which is critical to understanding regional flow systems. On the Mexican side, CONAGUA is currently conducting an update on the delimitation and systems of the dynamics of groundwater. The criteria being considered include both natural and administrative-geopolitical systems. However, there is still a need for further studies at the regional and local levels in Mexico, due to the fact that the commonly published information only refers to the local flow systems of shallow aquifers.

Furthermore, a significant limitation is the disparity in how the data is published, which has represented a substantial challenge. At the same time, other data related to groundwater are different in quality and quantity between the two sides of the USA/Mexican border. Standardizing this information is necessary to understand and compare the situation of each aquifer, not only for natural and physical environments of the aquifers, but for the socioeconomic, administrative, and legal issues in each geographical zone of this study; these are the basis of consecutive deliverables in this study.

The data and information in this report and the other two annexes represent a great opportunity for the APN region to significantly improve its water knowledge. This synthesis presents data and information fully sourced, with a preliminary analysis with their usefulness, associated scales, gaps, and recommendations on future research needs. Table 1 summarizes the domains, the existing information, and the gaps.

All the references and related bibliography cited in this report are listed in annex B.

1.1. Objectives

This report represents deliverable D1.2 under the pilot project. The main objectives of this report are:

- to compile, integrate and analyze existing data and information on the physical and chemical characteristics of the APN-TBA;
- to generate a common database;
- to analyze the data and identify the gaps and research needed to fill-in the gaps; and
- to recommend further data generation and collection necessary to build a conceptual hydrogeological model of the APN-TBA.

1.2. Data and information

The collected data and information are grouped into six domains: geology, hydrogeology, surface water, groundwater, hydro-geochemistry, and the environment. The following sections detail the main findings of the data collection for each domain; in each section, the reader is referred to annexes B and C where a complete and more detailed data and information can be found. The data and information in this report will be used to generate conceptual hydrogeological models at the local, intermediate, and regional scales at later stages of the project; these will help support the development of a three-dimensional numerical hydrogeological model in future phases.

1.3. Domains of study

Understanding the dynamics of groundwater flow (i.e., use and movement) requires knowledge of the governing processes and conditions from the local- to intermediate-, to the regional or basin-scales. The knowledge at those scales is crucial in understanding the role of groundwater flow from recharge to discharge areas in solving water management and environmental problems.

The study built a coherent framework with the data and information including all three scales to define inflows, outflows, and uses of land and water. The region under study, centered around the Allende - Piedras Negras aquifer, was divided into three extents to assess existing data and information for nested watersheds and aquifers: the 500-km scale (regional or basin), the 250-km scale (intermediate), and the 100-km scale (local), as depicted in Figure 1.

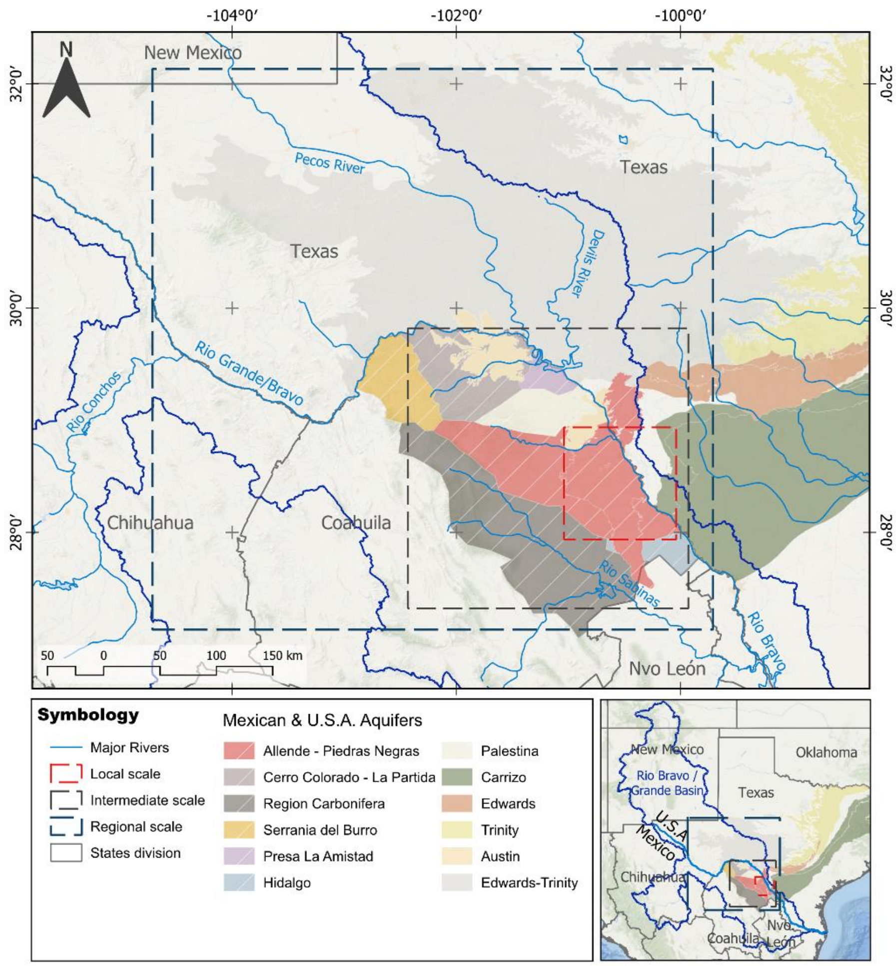


Figure 1. Region and spatial scales under study. Source: own elaboration from different data sources.

The larger scale includes most of the Edwards-Trinity regional-scale aquifer system on both sides of the US/Mexico border, as well as the main basins and rivers in the study area. The intermediate scale includes all of the Mexican-defined administrative aquifers, as well as the American-defined aquifers located closest to the US/Mexico border. The local scale includes basically the whole of the Allende-Piedras Negras Quaternary aquifer, for which considerable data, information, and studies exist.

Table 1 Summary of the information outline and data gaps for each aquifer. *Dark blue indicates complete information, light blue indicates partial information, and X indicates no data*.

Domain	**Information**	**Aquifers**									
		APN-Mex	APN-US	Región Carbonífera	Palestina	Serranía del Burro	Cerro Colorado	Hidalgo	Edwards-Trinity	Austin Chalk	Carrizo-Wilcox
Geology	Define structural geology										
	Define hydro-stratigraphy units at the three scales										
	Surface geophysical surveys		X	X	X	X	X	X	X	X	X
	Well-log geophysical surveys		X	X	X	X	X	X			
Hydrogeology	List and briefly describe existing aquifers at the three scales: regional, intermediate, and local – with thicknesses and horizontal extensions.										
	Generate 2D horizontal maps with aquifers boundaries at the regional scale										
	Create hydrogeological sections at the three scales										
	Aquifers' recharge and discharge, mechanisms, and values.									X	
	Aquifers' hydraulic parameters: Porosity, hydraulic conductivity, transmissivity, storage, specific yield, specific storage coefficient, specific capacity.										
	Groundwater flow systems										
	Existing conceptual and numerical models	X	X	X	X	X	X	X		X	
Surface water	Define and describe rivers, lakes, wetlands										
	Generate 2D maps with watershed boundaries at the regional scale										
	Locate hydrometric stations with runoff data										

	Present runoff data in table and graphical formats										
	Identify surface water users and volumes used								X	X	X
Groundwater	Define and describe soil water, aquifers, wetlands								X	X	X
	Identify groundwater users and volumes used								X	X	X
	Water levels, depth to water, water elevation										
	Generate or reproduce piezometric maps									X	
	Geobase information (GIS)										
	Nearby wells at different depths		X	X	X	X	X	X	X	X	X
Hydro-geochemestry	Surface water and groundwater quality										
	Water analysis: physicochemical parameters (EC, TDS, DO, redox potential, pH, Temp)										
	Isotopes (3H, 2H, 18O, 13C, 14C, 32S, Sr)	X	X	X	X	X	X	X			
	Dissolved anions and cations		X			X	X		X	X	X
	Water types (Piper, Stiff, ionic relations)										
	Halogens: F, Cl, Br	X	X	X	X	X	X	X	X	X	X
	Water dating	X	X	X	X	X	X	X		X	
	Ohers: Salinity, total organic carbon (TOC); DBO, DQO; total and fecal coliforms; organic compounds									X	
	Water quality degradation		X							X	
Environmental	Climate: precipitation, potential evaporation, ET, temperature										
	Land use and ownership										
	Pollution sources	X	X	X	X	X	X	X	X	X	X
	Groundwater-dependent ecosystems		X							X	X
	Solid waste and wastewater controls		X							X	

Remote sensing	Land and soil: Land use, vegetation indexes (NDVI, SAVI, InSAR), soil physical properties										
	Climate: Precipitation, Temperature, relative humidity, solar radiation, wind speed/direction									**X**	
	Hydrology: Soil moisture, PET, AET									**X**	
	Hydrogeology: existing GRACE studies, storage anomalies, correlations.										

2. DATA SOURCES

Most of the data used for this report come from official repositories of Mexican or United States federal institutions, which are described in Table 2. Because these databases will be frequently mentioned, the reader can consult the description and access links from this section.

Table 2. Description and URLs of the most important datasets, webpages, and interactive dashboards consulted to visualize and download the data used in this report.

Name	Description	Data or variables	Domains	Link
SINA	The National Water Information System (SINA) is an instrument for managing strategic information on water resources in Mexico, under the responsibility of the Water Planning Management of the General Directorate of CONAGUA.	Catchments and aquifers boundaries, water allocation, water availability, water quality	Hydrogeology, groundwater, surface water, hydro-geochemistry	Link
REPDA webpage	The Public Registry of Water Rights (REPDA) of CONAGUA provides information on the concessioned volumes of surface water and groundwater, the use of water, as well as construction information on wells and other uses.	Water use, location of wells	Hydrogeology, groundwater, surface water	Link
SIGAGIS webpage	The Aquifer Geographic Information System (SIGA) is a system that collects information related to groundwater in Mexico, managed by the Geographic Water Information Sub-Management of CONAGUA.	Groundwater levels, aquifer boundaries, regulations and reserves	Hydrogeology, groundwater	Link
SIH webpage	The Hydrological Information System (SIH) is a system that allows the visualization and download of climatological and hydrological data of the General Technical Sub-directorate, it contains recent and historical data from conventional and automatic climatological and hydrometric stations of the CONAGUA network and other Federal Government Agencies.	Precipitation, temperature, evaporation, streamflow, reservoirs conditions	Surface water, Environment	Link
BANDAS webpage	The National Surface Water Data Bank (BANDAS) of CONAGUA provides daily and sub-daily information from records at hydrometric stations in the country.	Streamflow records, location of streamflow gauges	Surface water	Link
SMN climatological statistics	This portal allows you to consult historical information from the conventional weather stations of the Mexican Meteorological Service	Precipitation, temperature, evaporation	Environment	Link

Name	Description	Data or variables	Domains	Link
	(SMN) that make up the CONAGUA National Network.			
INEGI website	The National Institute of Statistics, Geography and Informatics (INEGI) provides sociodemographic and economic indicators by geographic area	Population, socio-economic indicators, hydrology layers, among others	Surface water, Environment	Link
SGM geoportal	Interactive viewer of geological charts of the Mexican Geological Service (SGM)	Structural geological charts	Geology	Link
TWDB website	The TWDB website provides information about the Water Supply Planning in Texas, as well as several datasets and studies of water resources in the state	Water use, groundwater levels, water quality, catchments, and aquifers boundaries, location of wells and streamflow gauges, geology, administrative regions, water plans,	Geology, Hydrogeology, Surface water, Groundwater, Hydro-geochemistry, Environment	Link
Water Data for Texas	Interactive dashboard by the TWDB for visualize and download real-time data in Texas	Reservoirs conditions, drought indicators, groundwater levels	Surface water, Groundwater, Environmental	Link
The North American Atlas	The North American Atlas – Basin Watersheds data set shows watersheds in North America at 1:10,000,000	Boundaries of catchments in Canada, U.S.A and Mexico as shapefiles	Surface water	Link
National Water Dashboard	The National Water Dashboard is an interactive dashboard to visualize and download real-time data collected by the USGS	Streamflow, lake levels, reservoir conditions, precipitation, water quality, groundwater levels	Surface water, Groundwater, Environment	Link
USGS GageLocations	The USGS provide the location of ~26,000 surface water monitoring gaging stations in the U.S. as shapefiles	Location of streamflow gauges	Surface water	Link
NOAA Climatological Data	The NOAA National Centers for environmental Information provides this Local Climatological Data of weather and climate records in stations for the U.S.A since 2005	Precipitation, temperature, relative humidity, wind speed	Environment	Link
CHIRPS	Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) is a 35+ year quasi-global rainfall data set with a resolution od ~5 km. Spanning 50°S-50°N (and all longitudes) and ranging from 1981 to near-present.	Precipitation	Environment	Link

Name	Description	Data or variables	Domains	Link
MODIS 13A1	Moderate Resolution Imaging Spectroradiometer (MODIS) vegetation indices, produced on 16-day intervals and at multiple spatial resolutions, provide consistent spatial and temporal comparisons of vegetation indices.	Normalized difference vegetation index (NDVI) and Leaf area index (LAI)	Environment	Link
GLDAS2.2	NASA Global Land Data Assimilation System Version (GLDAS) 2.2 includes climate data from CLSM-F2.5 with Data Assimilation for the Gravity Recovery and Climate Experiment (GRACE-DA) to simulate several hydrological variables	Potential evapotranspiration, actual evapotranspiration, soil moisture, terrestrial water storage	Environment	Link
GLEAM	The Global Land Evaporation Amsterdam Model (GLEAM) provides estimate the different components of land evaporation.	Potential evapotranspiration, actual evapotranspiration	Environment	Link
NALCMS	The Noth America Land Change Monitoring System (NALCMS) is a collaboration of the USGS and other institutions in Canada and Mexico and provides land cover classes using Landsat images at 30 m of resolution for 2010, 2015, and 2020.	Nineteen land cover classes based on the Land Cover Classification System (LCCS)	Environment	Link
SRTM	The NASA Shuttle Radar Topographic Mission (SRTM) provides digital elevation data (DEMs) for over 80% of the globe with a resolution of 90m at the equator.	Terrain elevation	Surface water, Environment	Link

3. DOMAINS

3.1. Geology

To understand how groundwater infiltrates, is stored, it flows, is regulated, and is used, it is important to acquire knowledge of the geological and environmental conditions through which it flows.

3.1.1. Structural geology

The geological data for this study was obtained from Mexican Geological Survey (SGM, in Spanish), United States Geological Survey (USGS) and Texas Water Development Board (TWDB). Figure 2 shows Mexico and Texas's surface geology, faults, and structures. Data is obtained from SGM, USGS, and TWDB. **An important limitation** is the unification of geological information to relate similar formations.

At the **regional scale**, south-central Texas has three major structural elements: the Llano uplift (and its subsurface extension, the San Marcos arch), the Ouachita structural belt, and the Balcones fault zone. The Llano uplift has pre-Cambrian metamorphic and plutonic rocks exposed in its core, and the San Marcos arch is a broad anticlinal extension of the Llano uplift. The Ouachita structural belt is a late Paleozoic compressional tectonic province that was later subsided and buried by Mesozoic and Cenozoic rocks as the Gulf of Mexico opened and subsided. The Balcones fault zone is a system of high-angle normal faults with net displacement toward the Gulf of Mexico and constitutes the principal structural deformation affecting Edwards aquifer development. The structural setting of the Austin Chalk has been determined by the Gulf Coast geosyncline, and affected by the Balcones, Luling, Mexia, and Talco fault zones. Faulting throughout the Austin Chalk trend is characterized by en-echelon normal faults. The Balcones fault zone is a conjugate normal fault system whose trend closely approximates the Paleozoic Ouachita fold and thrust belt from Kinney County in southwest Texas to Dallas County in northeast Texas (Weeks, 1945). The Austin Chalk outcrop trend coincides with the Balcones fault zone (Corbett et al., 1987).

At the **intermediate scale**, the dominant structural features in the southern APN aquifer include the Rio Grande Embayment in the southwest, the San Marcos Arch to the northeast, and growth faults in the downdip area (Figure 3). The embayment promotes sediment deposition in the central area (Table 3). The axis of the Rio Grande Embayment coincides with the Frio River, located northeast of the APN aquifer (Schorr et al., 2021).

At the **local scale**, the Allende-Piedras Negras aquifer encompasses the "Región Montañosa de Coahuila" and "Cuenca del Bravo de la Llanura Cosera del Golfo de México" physiographic provinces. The area includes an alluvial plain, inclined towards the southeast and limited to the east by the Río Bravo and to the west and northwest to the Lomerío de Peyotes and by the Serranía del Burro. The aquifer contains rocks from the Quaternary to the Cretaceous period, with the Sabinas-Reynosa Formation being the most prominent within the plain.

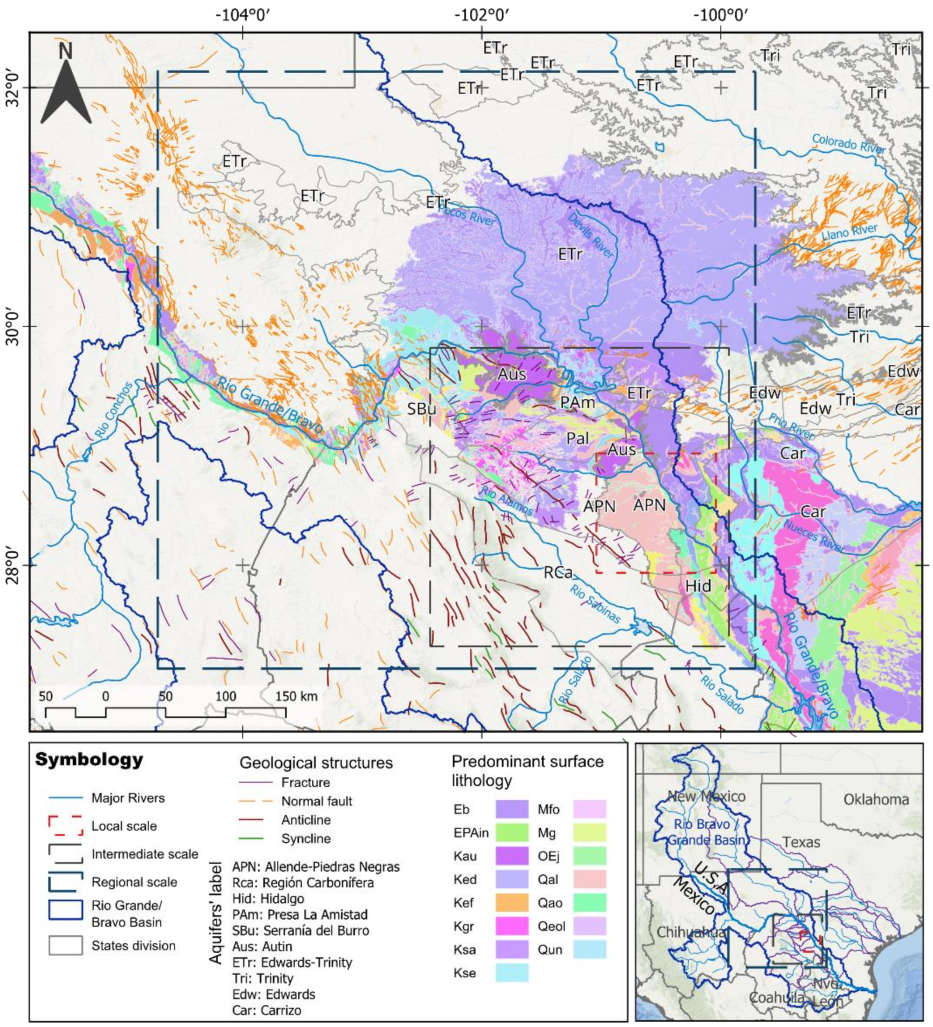


Figure 2. Surface geology and major faults. Source: own elaboration from different data sources.

In general, the stratigraphic column in all aquifers on the Mexican side shows two main hydrogeological units, an upper or shallow unit formed by unconsolidated materials and conglomerates, and a deep one formed of carbonate rocks from the Lower Cretaceous. The shallow and deep aquifers are separated by poorly permeable or impermeable formations from the Upper Cretaceous. The mountain massifs are configured by anticlinal and syncline folds with the main NW-SE orientation, which are cut by numerous faults. Under natural conditions, the shallow aquifers discharge water into rivers and streams that are tributaries of the Río Grande. Alternatively, they may discharge groundwater into the same river in some sections along the border, as is the case of the Allende-Piedras Negras aquifer.

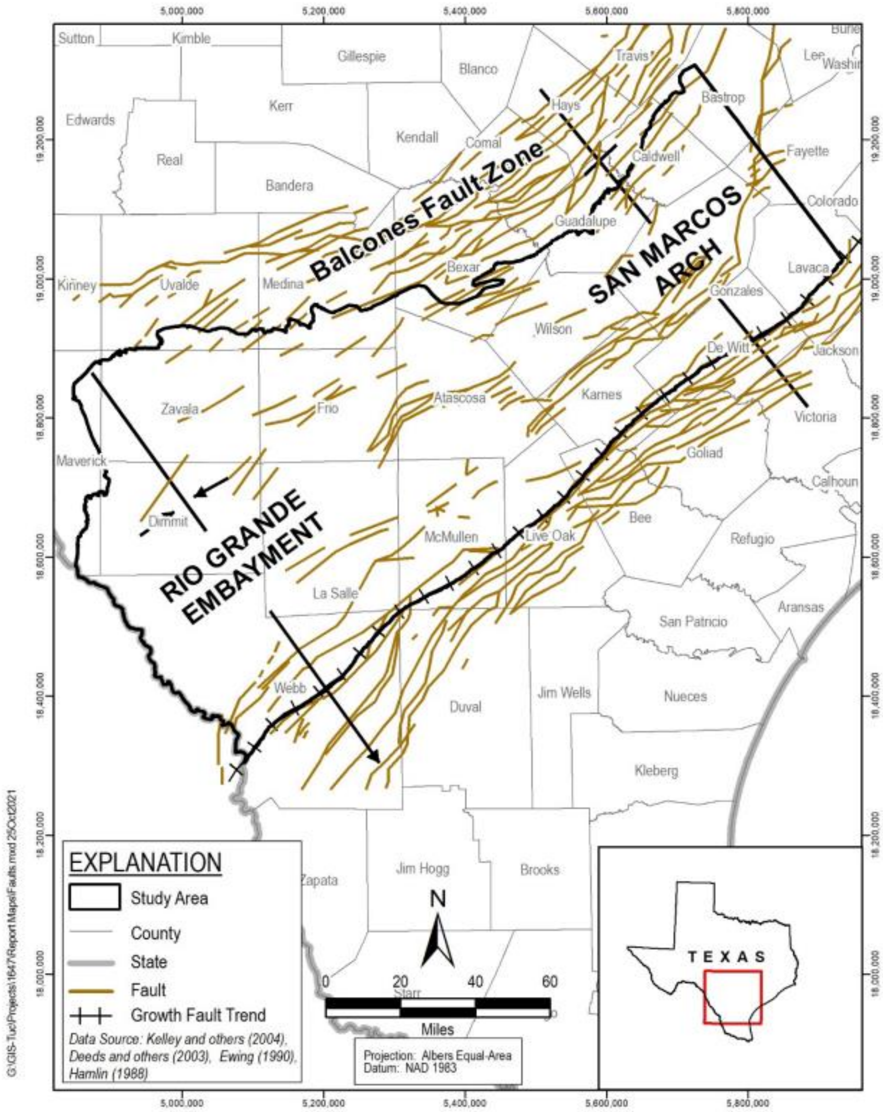


Figure 3. Major fault and structural features in the southern Carrizo-Wilcox aquifer (Schorr et al., 2021).

3.1.2. Hydro-stratigraphic units

The range in age from the Lower Cretaceous to the Recent of stratigraphic and hydrostratigraphic units **at regional scale** is listed in Table 3. Additionally, the stratigraphic column in the aquifers at the **intermediate scale** is composed of sedimentary rocks, including limestone, shale, sandstone, and dolomite, as listed in

Table *4*. The area is mostly dominated by shale-sandstone and shale-limonite formations. Only one formation comprises gypsum.

At the **intermediate scale,** there are two main formations, Taraises and Menchaca, from the Lower Cretaceous period. After these two formations, the Barril Viejo Formation follows, which is formed by shales, siltstones, marls, and sandy limestones. On top of this, is the La Mula Formation, which is formed of shale, sandstone, and siltstone. The La Virgen Formation follows and is composed of gypsum with alternating layers of mudstone and wackestone limestone. Finally, there is the Aurora Formation, which is formed of medium to massive, stratified limestones. The Kiamichi Formation is a sequence of shales with a calcareous member in the middle corresponding to a middle-upper Albian age. Above it, there are limestones and shales of the Washita group formations, ranging from the Upper Albian to the Lower Cenomanian. The Eagle Ford Formation is above the Washita group and contains calcareous shales with index faunal contents from the upper Cenomanian-Turonian age. The Austin Formation, which is composed of clayey limestones and shales, transitions onto the Eagle Ford Formation. The terrigenous formations overlap in the following order: the Upson Formation, the San Miguel Formation, the Olmos Formation, and the Escondido Formation.

The Midway Formation is found underneath the Allende-Piedras Negras and Hidalgo aquifers near the Rio Grande River. It is composed of Paleocene sediments including calcareous siltstones, sandy shales, limestone horizons, nodular clay, and concentrations of mollusks. Overlying the Midway Formation is the Eocene Wilcox Formation, composed of sandstones and shales. The Sabinas Formation, a conglomerate of limestone fragments, is assigned to a Miocene-Pliocene age. Volcanic rocks from the Pleistocene are located discordantly. Finally, recent deposits of the Quaternary age (Holocene) include foothill deposits and alluvium and lacustrine deposits covering the entire column.

The Allende-Piedras Negras aquifer encompasses the “Región Montañosa de Coahuila” and “Cuenca del Bravo de la Llanura Cosera del Golfo de México” physiographic provinces. At the **local scale**, the area includes an alluvial plain, inclined towards the southeast and limited to the east by the Río Bravo and to the west by the Serranía del Burro and the Lomerío de Peyotes. The aquifer contains rocks from the Quaternary to the Cretaceous period, with the Sabinas-Reynosa Formation being the most prominent within the plain. The Serranía del Burro is composed of limestone, marl, and shale from the Lower Cretaceous. The dominant geological structures in the area are the Serranía del Burro and Lomerío de Peyotes, which are anticlines formed during the Laramide orogeny. The Serranía del Burro is a dome-shaped structure with smooth slopes, where the Lower Cretaceous limestones emerge. The Lomerío de Peyotes has the same orientation and slippery slopes, with the outcrop of the limestones and shales of the Upper Cretaceous Austin Formation. Other important structural features include the NW-SE oriented rift that determines the course of the Río Bravo/Grande and the great normal fault called “El Cedral” which limits the aquifer to the south with a vertical displacement of 1,250 m. The plain subsoil has several secondary folds, a system of faults, and N-S and W-E orientation fractures.

Table 3. Stratigraphic and Hydrostratigraphic units on both sides of the U.S./Mexico border. (Modified from Hamlin, 1988; Smith, 1970; Bennett and Sayre, 1962; Rodriguez et al., 2020)

Era	**Period**	**Hydrostratigraphy**	**Mexico**		**U.S.A.**	
Cenozoic	Quaternary	APN Aquifer	**Qt Conglomerates (Mex and U.S.)**	**Qt Alluvium (Mex and U.S.)**	**Qt Colluvium (Mex and U.S.)**	**Modern Alluvium**
		APN Aquifer				**Uvalde Gravel (Mex and U.S.)**
	Neogene	APN Aquifer	**Reynosa Fm (Mex)**		Goliad Fm	
		APN Aquifer				
	Paleogene	Confining unit	Bigford Fm		Bigford Fm	
		Carrizo-Wilcox aquifer	Carrizo Fm		Carrizo Sand	
			Wilcox Fm		Indio Fm	
		Confining Unit	Midway Fm		Kincaid Fm	
Mesozoic	Cretaceous	Locally water bearing	Escondido Fm		Escondido Fm	
			Olmos Fm		Olmos Fm	
			San Miguel Fm		San Miguel Fm	
			Upson Fm		Upson Clay	
		Austin Chalk	Austin Fm		Austin Chalk	
		Austin Chalk				
		Confining unit	Eagle Ford Fm		Eagle Ford Gr	
		Locally water bearing units	Buda Fm		Buda Limestone	
			Salmon Peak Fm		Salmon Peak Limestone	Devils River Limestone
		Edwards Aquifer	McKnight Fm		McKnight Fm	
			West Nueces Fm		West Nueces Fm	
			Telephone Canyon Fm		Telephone Canyon Fm	
		Locally water bearing unit	Glen Rose Fm		Glen Rose Fm	

Table 4. Stratigraphic column of the area corresponding to the local and intermediate scales according to the delimitation of the aquifers under study. *The brown color identifies the lithology composing each aquifer*.

Formation	Lithology	APN	Región Carbonífera	Palestina	La Amistad	Serranía del Burro	Cerro Colorado La Partida	Hidalgo
	Alluvial	■	■	■	■	■	■	■
	Colluvial	■	■			■	■	■
	Lacustrine		■					■
Extrusive igneous rocks	Basalt			■			■	
	Andesite-Andesitic Tuff		■			■	■	
	Rhyolitic Tuff-Rhyolite		■			■		
	Basalt		■					
Intrusive igneous rocks	Gabro							
	Andesitic porphyry					■		
	Quartzmonzonite							
	Diorite-Syenite			■			■	
	Granite-Diorite							
	Granite-Monzonite			■			■	
	Granite-Syenite					■	■	
	Monzonite							
	Andesitic porphyry		■	■		■	■	
	Rhyolitic porphyry		■			■	■	
	Granitic porphyry							
	Quartzlatite							
Reynosa Conglomerate	Polygenic conglomerate	■		■	■		■	■
Sabinas Conglomerate	Monogenic conglomerate	■	■					
Wilcox	Sandstone-Shale	■						■
Midway	Shale-Sandstone	■						■
Escondido	Siltstone-Sandstone	■	■					■

Formation	Lithology	APN	Región Carbonífera	Palestina	La Amistad	Serranía del Burro	Cerro Colorado La Partida	Hidalgo
Olmos	Shale-Sandstone	■	■					■
San Miguel	Sandstone-Shale	■	■					■
Upson	Shale-Siltstone	■	■					
Austin	Limestone-Shale	■	■	■	■		■	■
Austin-San Vicente	Limestone-Shale							
Eagle Ford	Shale-Limestone	■	■	■	■	■	■	■
Buda	Limestone	■	■	■	■	■	■	
Del Río	Shale-Limestone	■	■	■	■	■	■	
Salmon Peak-Santa Elena-Georgetown-Loma de Plata	Limestone	■	■			■	■	
Salmon Peak	Limestone	■	■	■	■	■	■	
Kiamichi	Shale-Limestone	■	■	■		■	■	
McKnight-Benevides-Kiamichi	Shale-Limestone	■	■			■	■	
Aurora	Limestone-Dolomite		■					
West Nueces-Bronce-Telephone-Canyon	Shale					■	■	
Edwards	Limestone-Shale	■	■	■		■	■	
West Nueces	Shale	■	■	■			■	
Glen Rose	Limestone-Marl	■	■	■			■	
Glen Rose-Benigno	Limestone-Marl					■	■	
La Peña	Limestone-Shale	■	■					
Cupido	Limestone	■	■					
La Virgen	Gypsum-Limestone		■					
La Mula	Shale-Limestone	■	■					
Barril Viejo	Shale-Limestone		■					
Menchaca	Limestone-Shale		■					
Taraises	Limestone-Shale		■					

3.2. Hydrogeology

3.2.1. Aquifers and hydraulic properties

The boundaries of aquifers in Mexico and Texas (Figure 4) were obtained from CONAGUA and TWDB, respectively. The Mexican legislation designates the basin and the aquifer as the basic units for the management of water resources. CONAGUA is currently updating the dimensions of the aquifers. This update uses six criteria to determine aquifer boundaries and hydraulic connections between hydrogeological units. These criteria include hydrographical, geological, hydrogeological, geomorphological, administrative, and geopolitical factors. Thus, the administrative and geopolitical criteria complement the technical-scientific criteria to help define the conventional limits for the evaluation, management, and administration of national subsoil waters. Nevertheless, there are still several gaps on the delimitation of the aquifer boundaries, definition of groundwater flow systems, interconnection between aquifers, and the behavior of hydraulic interconnection between hydrogeological units (i.e. multi-layer groundwater systems).

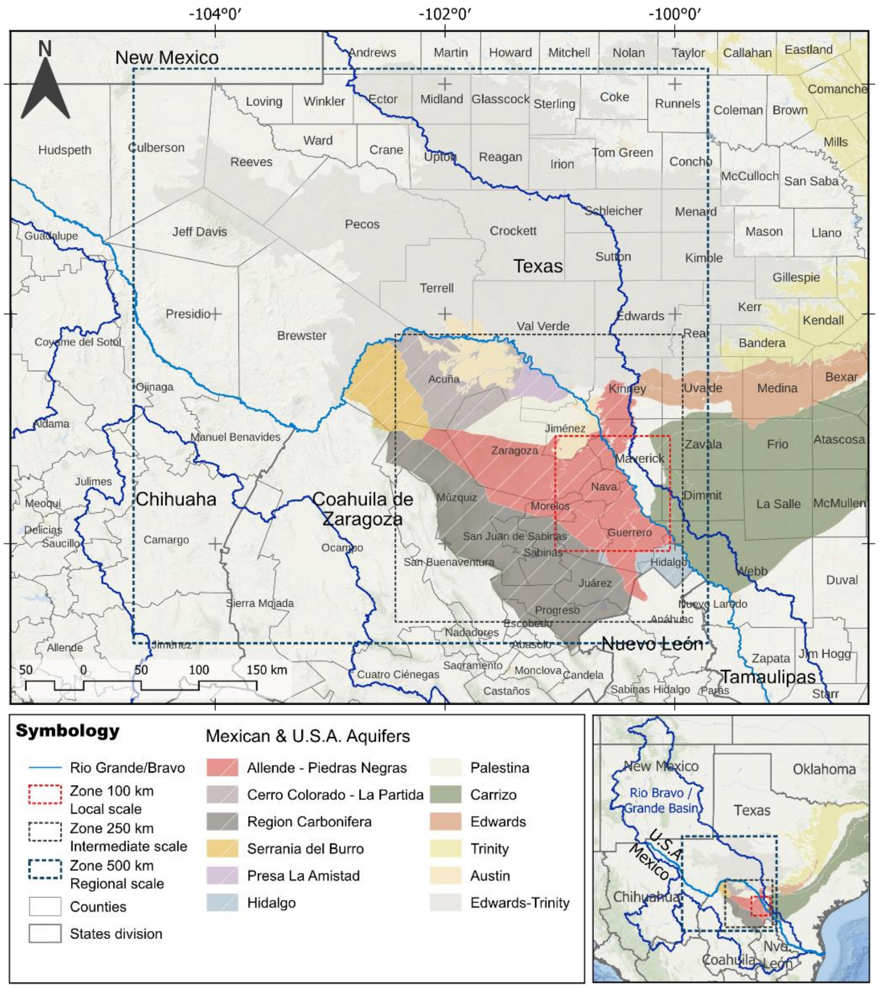


Figure 4. Extension of aquifers in Mexico and the USA. Source: own elaboration from different data sources.

On the other side of the border, U.S.A aquifers are defined based on geological units, and studies generally cover their entire extent, or a specific portion of the aquifer, depending on hydraulic boundaries.

At an **intermediate level**, Mexico side, it has been reported that the aquifers comprise of at least two hydrogeological units, however, **their dimensions remain unknown**. Additionally, the Allende Piedras Negras, Región Carbonífera, and Hidalgo aquifers are currently being over-exploited. Following official definitions by the Gerencia de Aguas Subterráneas of CONAGUA, an aquifer is considered overexploited when the amount of water extracted is 10% (or more) higher than the average annual recharge; this condition must persist for long periods and have noticeable environmental impacts. The primary recharge areas for most of the aquifers at this scale in the present study are attributed to precipitation infiltration in areas adjacent to the Sierra del Burro (except for Hidalgo aquifer), as well as returns from irrigation. Moreover, there are various springs found in the Sierra del Burro, which are attributed to local flows.

The hydraulic parameters for each aquifer are shown in Table 5; they vary significantly among the nine aquifers. Likewise, Figure 5 shows the spatial distribution of an estimation of hydraulic conductivity at **intermediate scale**. The APN and Carrizo-Wilcox aquifers show the largest capacity to allow the flow of groundwater, represented by hydraulic conductivity and transmissivity (Table 5).

Table 5. Aquifers' hydraulic parameters. Source: own elaboration from different data sources

Aquifer	Storage (Mm3)	hydraulic conductivity (m/s)	Transmissivity (m^2/s)	Water table (m)	Hydraulic head (masl)	specific storage coefficient	Estimation of water availability (Mm3)
Serrania del Burro		-	0.3^{-3} - 2^{-3}	-	-		10.66
Región Carbonífera		10^{-6} - 10^{-2}	0.23^{-3} - 175.3^{-3}	5 - 30	250 - 600	0.01 - 0.2	-32.04
Palestina		-	-	10 - 70	220 - 420		6.74
Hidalgo		-	-	10 - 60	-		-0.37
Edwards-Trinity (Plateau)	55,506	-	3.5^{-5}	-	-		
Edwards (Balcones fault zone)	26,603	-	-	-	-		
Cerro Colorado		-	-	100 - 140	-		5.50
Carrizo - Wilcox	6415	3.5^{-8} - 1.4^{-2}	1.1^{-7} - 1.1^{-2}	-	-		
Allende-Piedras Negras		-	20^{-3} - >40^{-3}	3 - 30	220 - 410	10^{-2} - 10^{-4}	-35.22

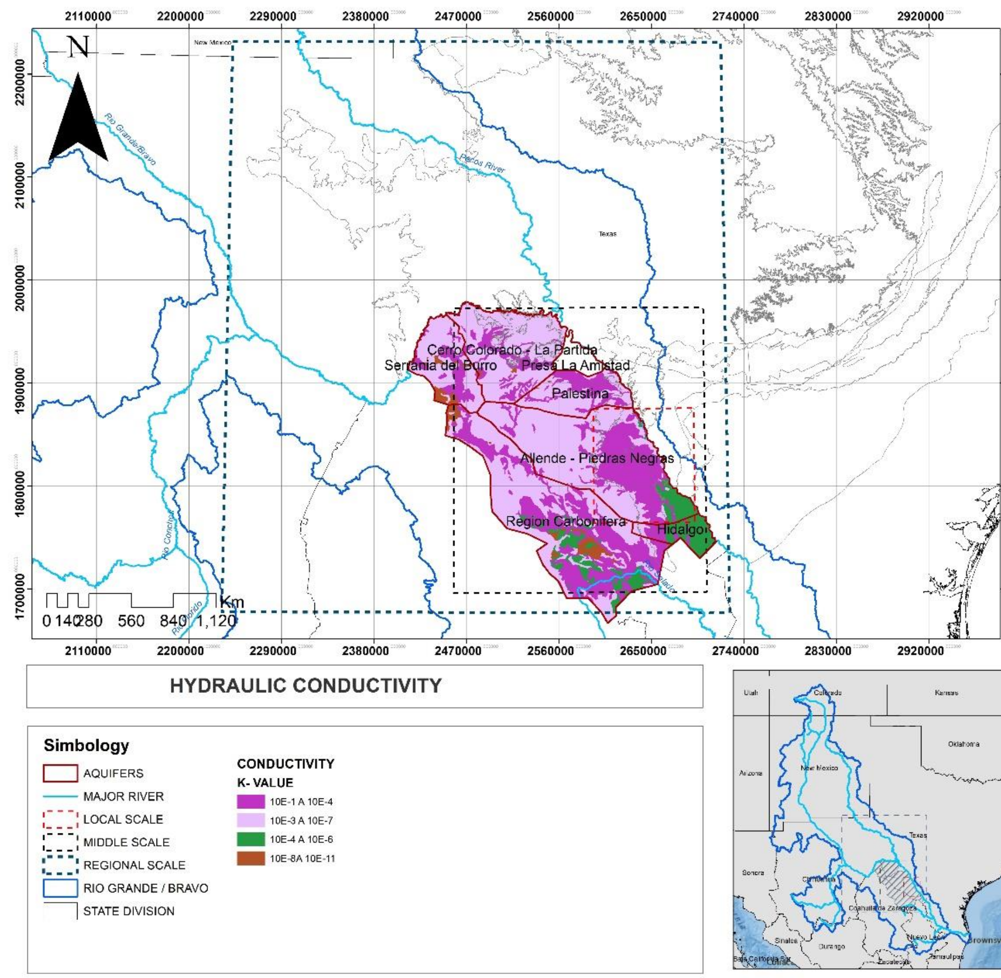


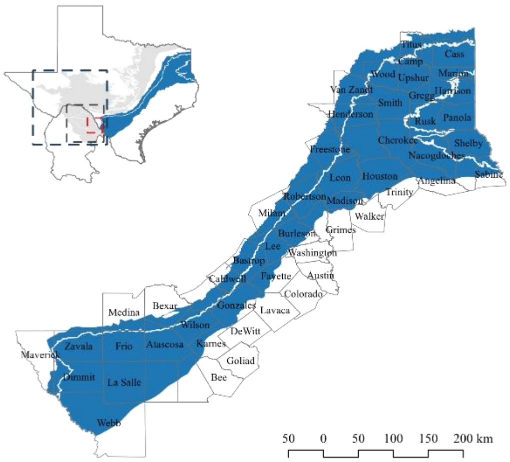
Figure 5. Hydraulic conductivity at intermediate scale. Source: own elaboration with data from INEGI.

At the **local level**, the Allende-Piedras Negras aquifer includes two hydrogeological units, which are described based on their geology, but with limited hydraulic data. Furthermore, the information about the water volume in store for each hydrogeological unit is currently unavailable.

At the **intermediate and local level**, **there is a lack of information regarding the hydraulic parameters** necessary to create a conceptual and numerical models for each hydrogeological unit in a spatiotemporal manner. This information is necessary to determine the actual availability per hydrogeological unit, as well as to develop comprehensive management plans.

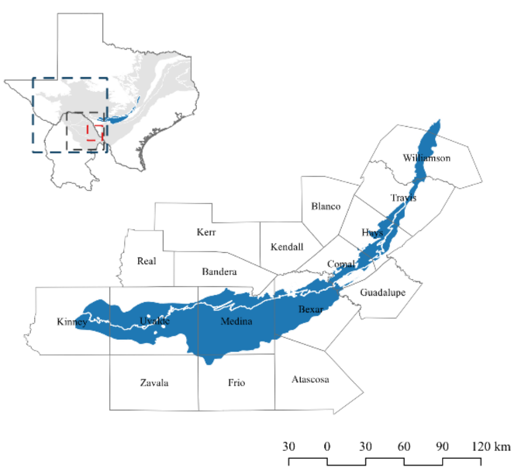
The following section briefly describes the aquifers at **three scales, regional, intermediate, and local**; including their thicknesses and horizontal extensions with aims to summarize the most relevant information and the lack of information:

Carrizo – Wilcox aquifer



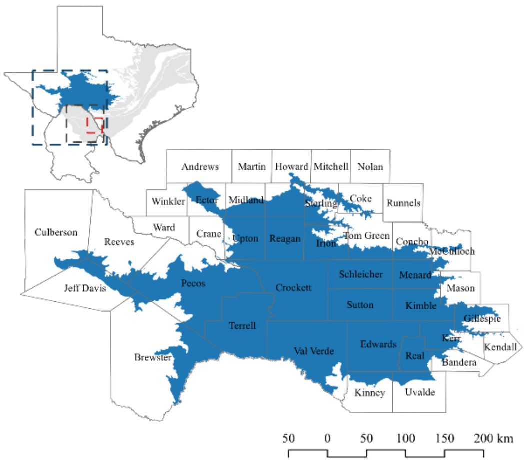
Aquifer type: confined and unconfined
Outcropping area: 29078 km^2
Subsurface area: 66021 km^2
Proportion of aquifer with Groundwater Conservation District (GCDs): 65%
Number of counties covering the aquifer: 66
It consists of the Hooper, Simsboro, and Calvert Bluff formations of the Wilcox Gr, and the overlying Carrizo Fm of the Claiborne Group.
Primarily composed of sand locally interbedded with gravel, silt, clay, and lignite.
Although the Carrizo-Wilcox Aquifer reaches 3,000 feet in thickness, the freshwater saturated thickness of the sands averages only 670 feet.

Edwards aquifer



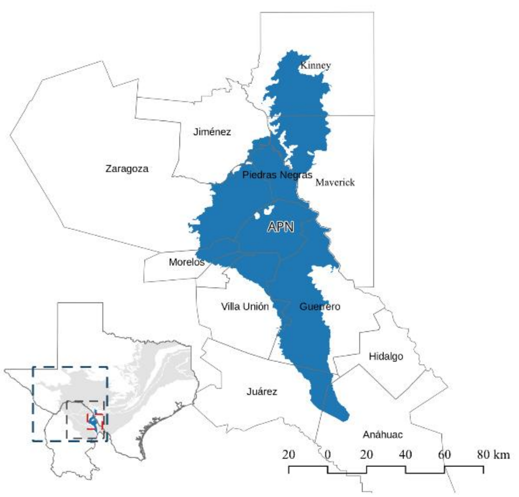
Aquifer type: confined and unconfined
Outcropping area: 4056 km^2
Subsurface area: 6426 km^2
Proportion of aquifer with Groundwater Conservation District (GCDs): 87%
Number of counties containing the aquifer: 14
consists primarily of partially dissolved, or karstic, limestone that creates a highly permeable aquifer.
Aquifer thickness ranges from 200 to 600 feet, and freshwater saturated thickness averages 560 feet in the southern part of the aquifer.

Edwards-Trinity (Plateau) aquifer



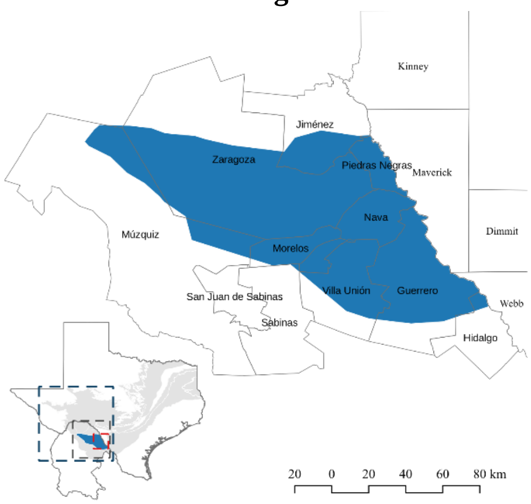
Aquifer type: mostly unconfined with small, confined areas
Outcropping area: 32,373 square miles
Subsurface area: 3,051 square miles
Proportion of aquifer with GCDs: 82 %
Number of counties covered by the aquifer area: 1.
Water bearing units: limestone and dolomite of the Edwards Group and sands of the Trinity Group.
Freshwater saturated thickness averages 433 feet.
The saturated thickness of the aquifer system generally increases from less than 100 feet in the north to greater than 800 feet down-dip to the south.
Saturated thickness is influenced by ridges and troughs in the underlying Paleozoic depositional surface and variation in the surface topography (Barker and Ardis, 1996).

Allende Piedras Negras aquifer U.S.A side



Aquifer type: unconfined and semiconfined in the lower section
1,597 km^2 in the U.S.A.
Number of counties covered by the aquifer area: 12.
Water bearing units: Goliad Fm and Uvalde Gravel.
Freshwater saturated thickness averages 25 m.
Locally saturated thickness is influenced by the connection with underlying limestones.

Allende Piedras Negras Mexican side

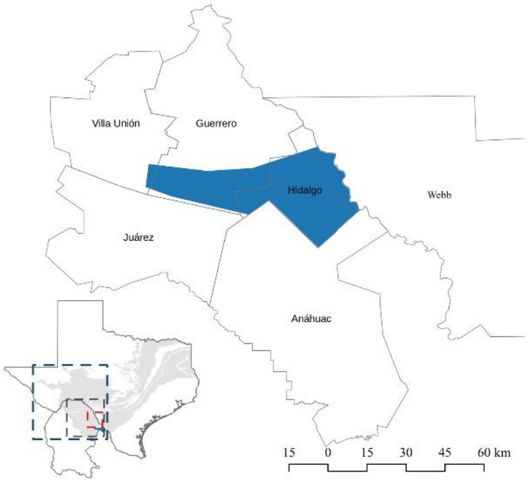


Aquifer type: confined, heterogeneous, and anisotropic. With an area of 12,961 km² in Mexico
Water bearing units: Two units, a shallow aquifer made up of unconsolidated alluvial materials, conglomerates and caliche, and a deep aquifer made up of Lower Cretaceous limestones. The upper portion has a few tens of meters of thickness, alluvial and fluvial sediments, and polymictic conglomerates. The lower portion is in a sequence of calcareous-clayey marine sedimentary rocks, which present secondary permeability due to fracturing and dissolution in the case of limestone.

Freshwater saturated thickness values vary between 5 and 25 m, which increases from the plain and the areas close to the beds of rivers and streams towards the topographically higher regions. Values of 5 to 7 m are recorded northeast of this aquifer.

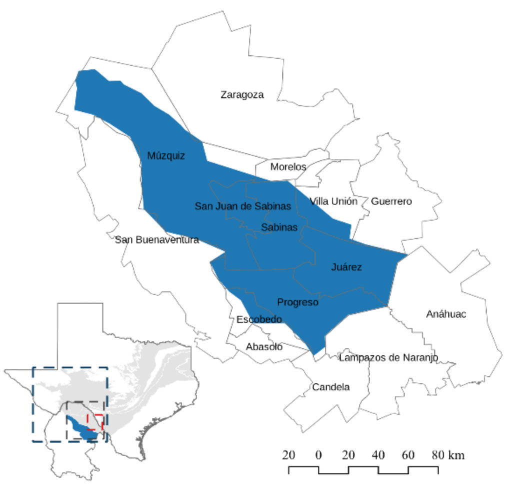
Saturated thickness is influenced by artificial recharge from the pits due to the return of water from the mines and in the vicinity of the Río Bravo. To the southeast of Nava, shallow point values occur due to both the low topography of the terrain and the infiltration of irrigation returns into the agricultural area, while to the west of Morelos the water levels depend of topography. Both hydrogeological units are only hydraulically connected on the flanks of the mountain ranges, where the Upper Cretaceous formations thin so that water from the deep aquifer circulates through them to feed the shallow aquifer.

Hidalgo aquifer



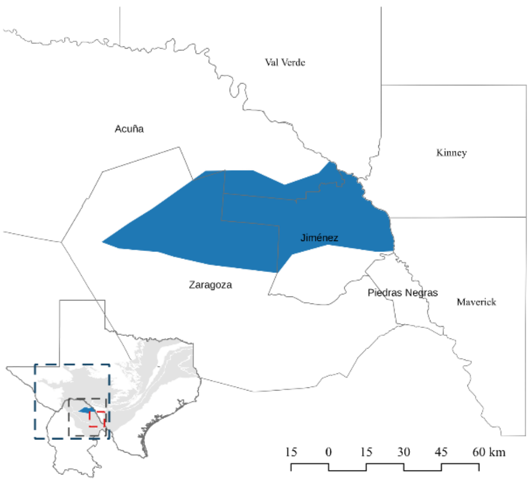
Aquifer type: confined, heterogeneous, and anisotropic.
1656 km²
Water bearing units: not defined.
Freshwater saturated thickness not defined.
Saturated thickness not defined.

Región Carbonífera aquifer



Aquifer type: confined, heterogeneous, and anisotropic.
15,754 km²
Water bearing units: Two units. The upper portion is composed of alluvial and fluvial sediments of varied granulometry and conglomerates, whose thickness can reach several hundred meters towards the center of the valleys. The lower unit consists of fractured calcareous-claystone from the Upper Cretaceous. The lithology includes alternating shales and siltstones, resulting in semi-confined or confined conditions due to secondary permeability caused by fracturing.
Freshwater saturated thickness values vary between 5 and 30 m. Piezometric information shows that depths between 10 and 20 meters are the most common, with only a few isolated locations reaching depths of 30 meters. In certain areas of the Barroterán region, the static water level is less than 5 meters deep.
Saturated thickness originates in rainfall over the valley and infiltration along surface runoff.

Palestina aquifer



Aquifer type: confined, heterogeneous, and anisotropic.

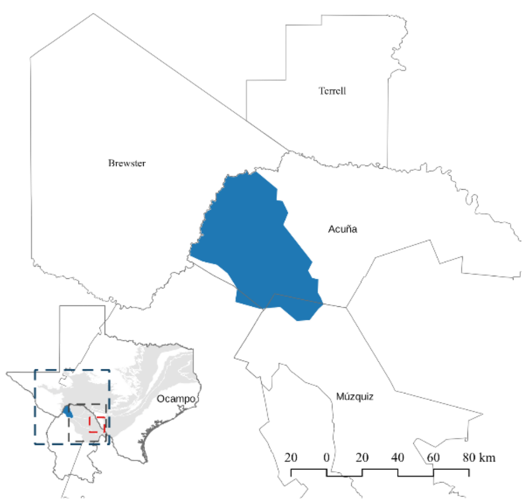
3,401 km²

Water bearing units: Two units, it is constituted in its upper portion by alluvial sediments and polymictic conglomerates, which outcrop predominantly to the east and whose thickness can reach a few tens of meters towards the center of the valleys. In its lower portion, there is a sequence of calcareous marine sedimentary rocks, that emerge predominantly to the west, forming part of the Sierra del Burro, and that present secondary permeability due to fracturing and dissolution, its thickness can reach a few hundred meters. The limestones constitute horizons aquifers that present confinement conditions, its lithology includes alternations with shales.

Values of freshwater saturated thickness vary between 10 and 70 m.

The saturated thickness varies depending on infiltration from precipitation.

Serranía del Burro aquifer



Aquifer type: confined, heterogeneous, and anisotropic.

4,016 km²

Water bearing units: Two units, its upper portion, by alluvial sediments of varied granulometry and very reduced thickness. This aquifer is currently exploited in the valley, which is little influenced, mainly through springs that only satisfy the needs of domestic use. The second unit is a deeper limestone-shale interbedded packages represent a potential source of groundwater that has yet to be explored.

Freshwater saturated thickness not found.

Saturated thickness originates from rainfall over the valley and infiltration from surface runoff.

Cerro Colorado aquifer

Aquifer type: confined, heterogeneous, and anisotropic.
7201 km²
Water bearing units: The upper portion is composed of alluvial sediments of varied granulometry and very reduced thickness.
Freshwater saturated thickness vary from 100 to 140 m.
Saturated thickness originates from rainfall over the valley and infiltration from surface runoff.

3.2.2. Conceptual models

Conceptual models are fundamental tools in hydrogeology, they are useful in representing the main hydrological/hydrogeological processes, indicating water inputs, outputs, interactions with other aquifers or bodies of water, and preferential water flows, among other characteristics. Conceptual models are, therefore, critical for the construction of numerical models.

At the **regional scale**, integrated conceptual models have been established for the Edwards-Trinity (Figure 6), Edwards (Figure 6), and Carrizo-Wilcox aquifers. These models have served as a basis for estimating the water balance in each aquifer and for determining the interaction between aquifers.

In the case of the Edwards-Trinity aquifer (Figure 6), the recharge zones were identified in high areas to the northwest of the aquifer, and with important discharge zones in the Pecos Valley, in interactions with rivers in the north-central area of the aquifer, and important volumes discharge to the Trinity and Edwards aquifer to the southeast.

The conceptual model of the Edwards aquifer suggests that heading toward the Gulf of Mexico (Figure 7), its hydrostratigraphic units extend beneath more recent formations, and subsurface flow recharges deeper units. Furthermore, the presence of fractured limestone allows high recharge rates in the west of the aquifer, where the main discharge areas to the surface occur through springs.

At the **regional scale**, the most important groundwater flows are from the Edwards-Trinity aquifer to the Pecos Valley aquifer in west Texas, from the Edwards-Trinity aquifer to the Edwards, and from the Edwards to the Carrizo-Wilcox aquifer, as shown in the Figure 8. According to this information, the discharge of water to the Rio Grande could be much lower from these aquifers. Thus, water contributions from different rivers that feed the Rio Grande could be decisive for maintaining the flow in the Rio Grande.

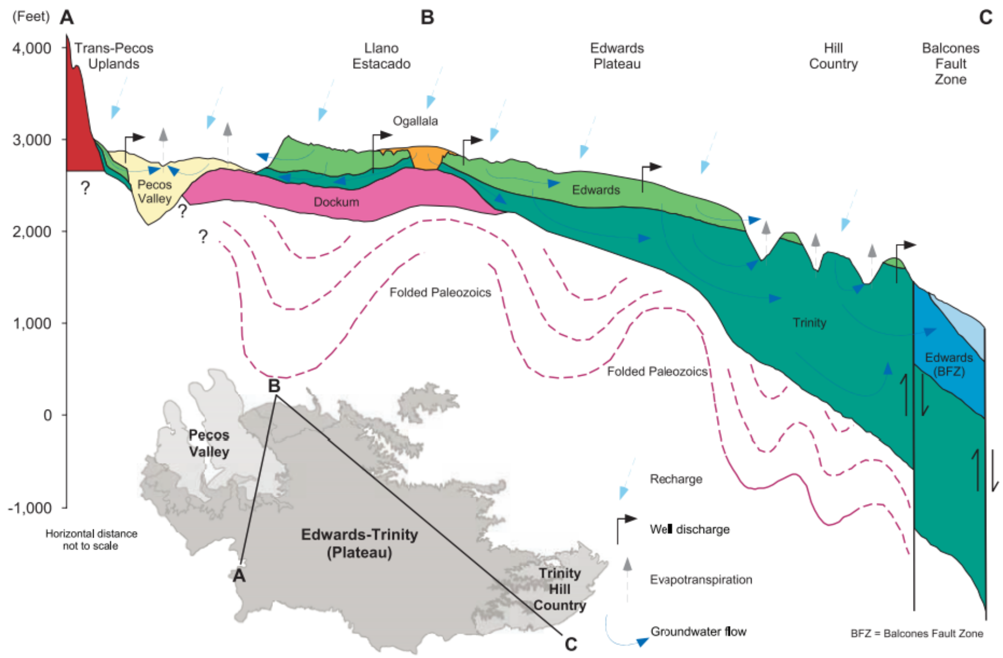


Figure 6. Conceptual model of the Edwards-Trinity (Plateau) and Pecos Valley aquifers and Hill Country part of the Trinity Aquifer (Jones et al., 2009).

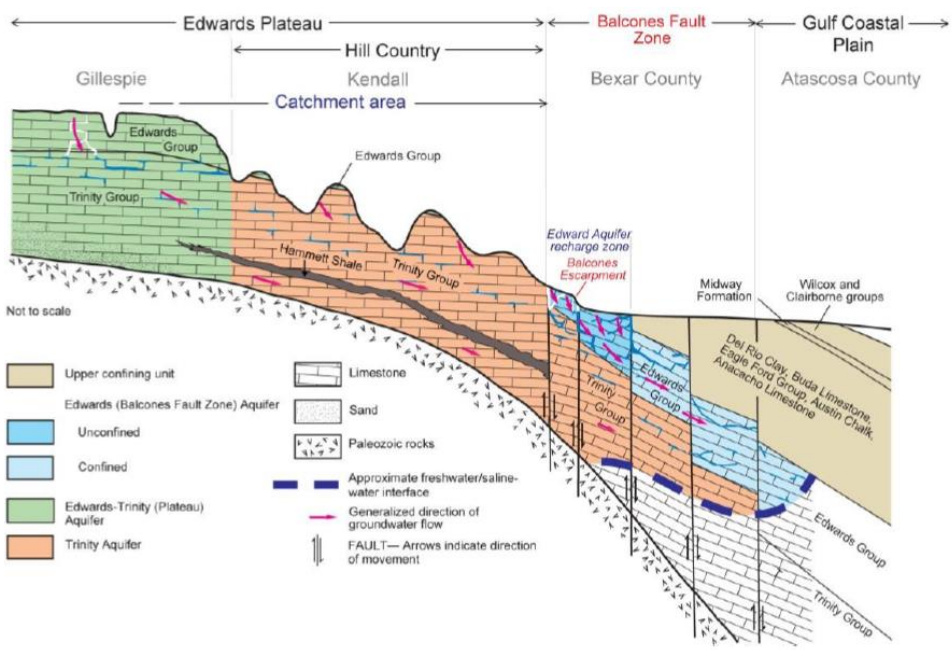


Figure 7. Conceptual model of the Edwards aquifer, San Antonio Region, Texas. Source: Bruun et al. (2016).

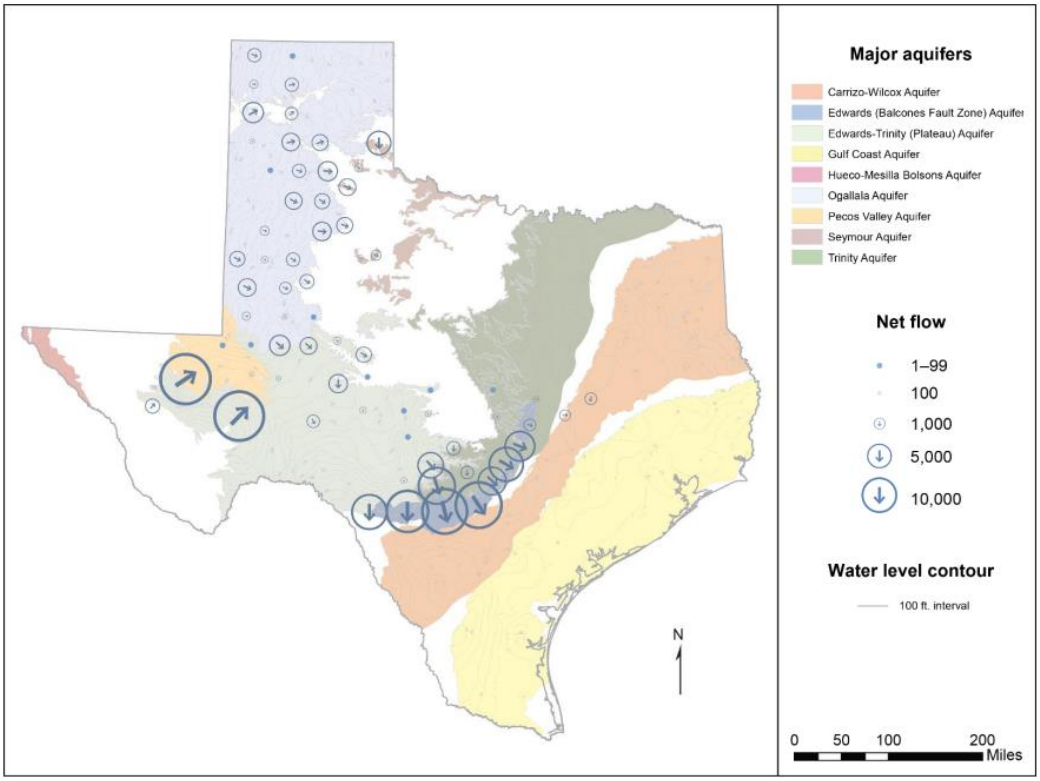


Figure 8. Groundwater fluxes between major aquifers in Texas. Arrow size is proportional to average annual flow. Net flow units are in Acre-ft/year. Source: Bruun et al. (2016).

In Mexico, **at an intermediate scale**, there are a few aquifers on the border with the USA that have established a conceptual model of the groundwater flow systems, as is the case for the Region Carbonifera aquifer (Figure 9) and Allende – Piedras Negras aquifer (Figure 10).

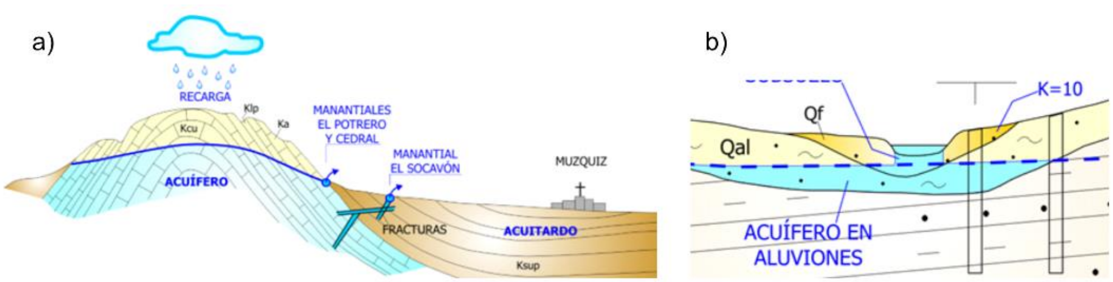


Figure 9. Conceptual model of the Region Carbonifera aquifer at a) the recharge zone in the limestones, and b) in a cross section of the Sabinas River in the alluvial aquifer (Lesser y Asociados, 2011a).

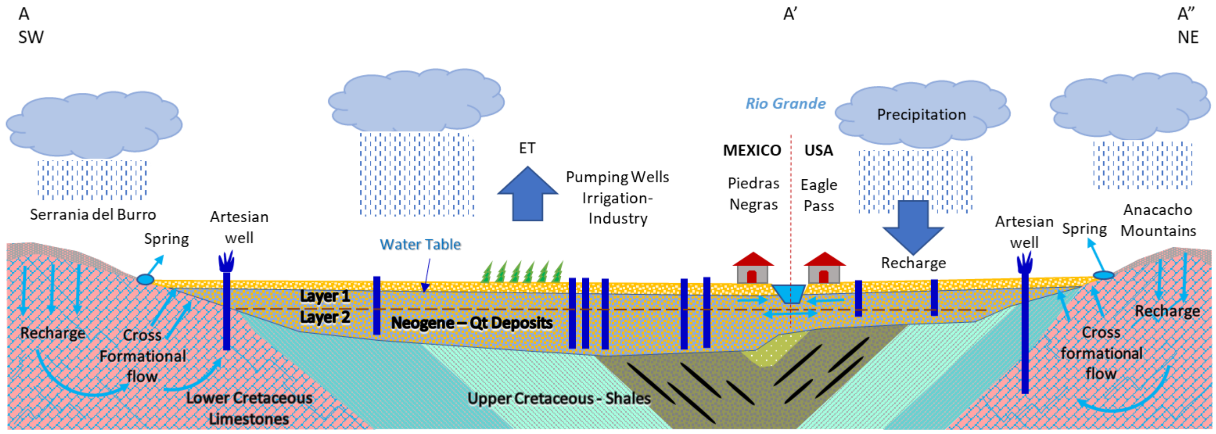


Figure 10. Conceptual model of the APN aquifer. Modified from Rodriguez et al. (2020). Unpublished.

The Región Carbonífera and Allende – Piedras Negras aquifers consist of two flow systems: one shallow and thin made up of alluvial deposits and conglomerates, which is where most of the groundwater extractions occur; and a deep flow system, made up mainly of limestone, which is recharged in the Serranía del Burro mountain range interconnected with the shallow aquifer through the discharge of springs originated by fractures, and in some cases by deep artesian wells. The groundwater recharge zone from which groundwater flows radially is generated in the Serranía del Burro, Palestine, Presa la Amistad, and Allende Piedras Negras aquifers, as shown in Figure 11. **This regional flow has not been properly analyzed due to limited information**; it is unknown whether it continues N-NE towards the Texas aquifers.

In the aquifers of intermediate scale, the Servicio Geológico Mexicano (SGM) has published geological sections to establish the structural geology; however, it is necessary to establish the recharge zones, discharge, connection between layers, among other characteristics to understand how groundwater moves in the aquifers. Moreover, due to the larger thickness of the hydrostratigraphic units, deep aquifers represent a critical water source for the region; however, there is a lack of information to understand these flow systems.

On the other hand, the existing interactions between the aquifers of Mexico and the USA still need to be studied in detail. This represents an important source of knowledge for a sustainable management of surface and groundwater; as it has been observed in the U.S.A., subsurface flows through aquifers can have magnitudes much larger than what are observed as surface-groundwater interactions Rodriguez et al. (2020).

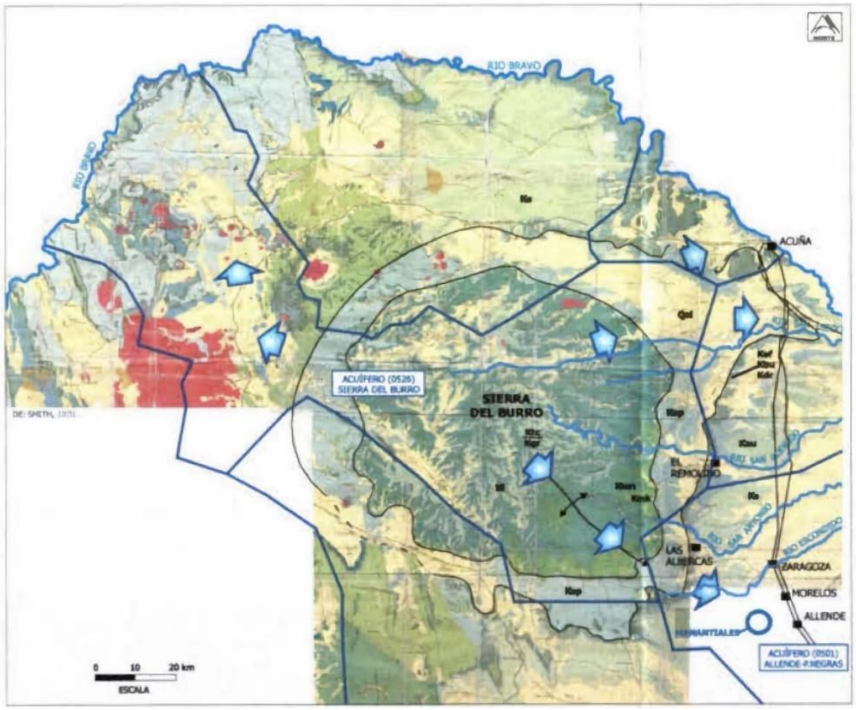


Figure 11. Recharge areas and deep groundwater flow at the intermediate scale. Source: Lesser y Asociados (2008).

3.2.3. Aquifers' recharge values

Groundwater recharge represents critical information for the sustainable management of aquifers, which includes among others, water supply, land subsidence, drought impacts, and springs flow.

Despite the importance of recharge, there is a **lack of groundwater recharge values** because recharge cannot be measured directly at the scales defined in this study, it must be inferred using different techniques; for example, from variations in the groundwater level, using water balances and chemical data. All these methodologies usually require information that, in many cases, is not available. Therefore, obtaining recharge values that cover a sufficient spatial and temporal extent is challenging.

At regional scale, for the aquifers located on the U.S.A. side, the main techniques used to estimate the recharge are Darcy's law, groundwater modeling, and baseflow discharge. Darcy's law is widely applied in the confined sections of the Carrizo-Wilcox and Gulf Coast aquifers. Groundwater modeling is used in most aquifers. Baseflow discharge is used primarily in the Edwards-Trinity and alluvial aquifers.

Estimation recharges in the Carrizo-Wilcox aquifer range from 2.54 to 147.32 mm/year. The higher recharge rates occur in the sandy portions of the aquifer (Carrizo sections), and higher recharge rates are in upland areas with sandy soils. Recharge rates in the Trinity and Edwards-Trinity aquifer generally range from 2.54 to 50.8 mm/year. Recharge rates for the Alluvial aquifers are represented as total recharge along mountain fronts and valley floors (Scanlon, Dutton, Sophocleous, 2002).

At the **intermediate scale**, CONAGUA reports an annual groundwater recharge estimation derived from groundwater level fluctuations within a water balance area representing a portion of the aquifers' boundaries (Table 1). However, these values have limitations, such as the lack of a periodic update.

Advanced spatial methodologies are available to estimate the recharge areas of an aquifer. These methodologies consider factors such as precipitation, evapotranspiration rates, and topographic and lithological characteristics. Table 6 provides the components to estimate the recharge areas of the aquifers along with the recharge values provided by CONAGUA. The recharge areas were determined using climatological data from the UNAM Digital Climate Atlas of Mexico (http://atlasclimatico.unam.mx/atlas/kml/) for precipitation; the Turc equation for evapotranspiration; and the methodology established in NOM-011-CONAGUA-2015 for calculating runoff (Mendieta-Mendoza et al., 2021). Figure 12 and Figure 13illustrate the spatial variation of recharge areas in the Allende Piedras Negras and Región Carbonífera aquifers, which have the highest recharge areas at an intermediate scale. These recharge areas are located in regions with low runoff, high hydraulic conductivity (10^{-1} to 10^{-3} m/s), and moderate hydraulic conductivity (10^{-3} to 10^{-7} m/s), corresponding to alluvial and limestone lithology, respectively. Thus, the main recharge areas for these two aquifers are in the Serrania del Burro and Lomerio Peyotes, as well as in agricultural zones.

Nevertheless, the recharge values require further research to estimate accurately.

Table 6. Water balance fluxes and recharge estimations.

Variable	Allende Piedras Negras	Cerro Colorado	Hidalgo	Palestina	Región Carbonífera	Serranía del Burro
Evapotranspiration (mm/year)	164-505	272-340	164-366	285-456	277-659	257-326
Precipitation (mm/year)	157-516	265-337	157-360	278-457	270-715	249-336
Maximum temperature (°C)	21-30	21-29	28-29	25-30	21-30	18-30
Medium temperature (°C)	15-23	15-21	20-22	18-22	15-23	12-21
Minimum temperature (°C)	8-15	8-14	13-15	11-15	8-16	5-13
Runoff (mm/year)	0-31	0-31	0-25	0-25	0-31	0-31
***Recharge (Mm^3/year)**	496.5	9.6	3.6	10.3	84.1	11.9

***** Values obtained from CONAGUA, 2020.

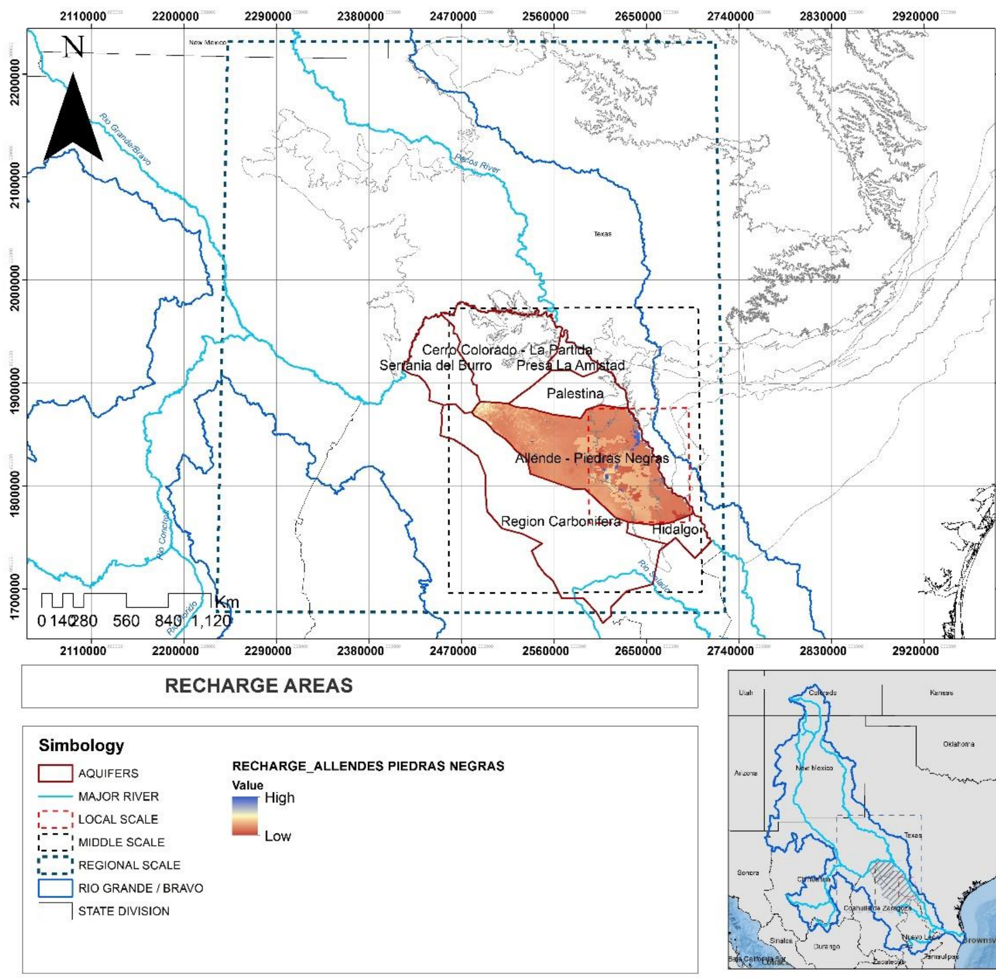


Figure 12. Estimation of recharge areas in the Allende Piedras Negras aquifer. Source: own elaboration.

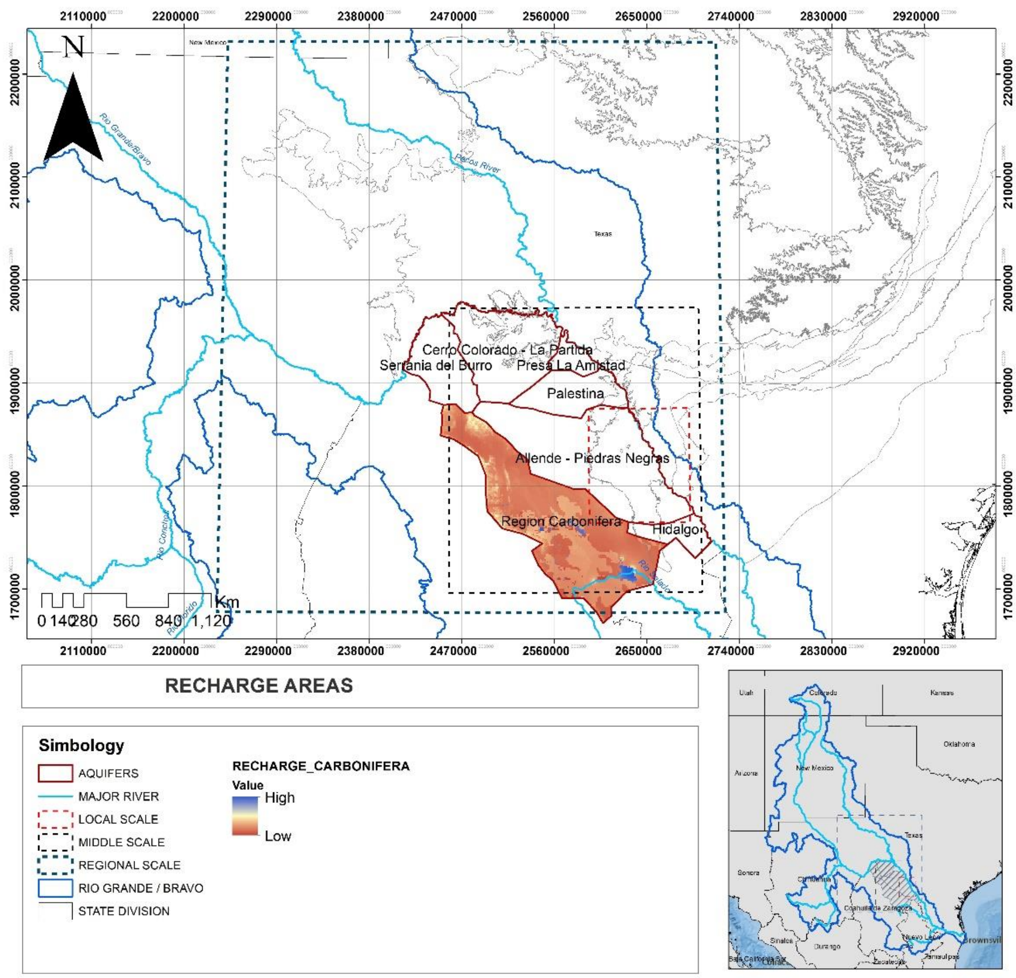


Figure 13. Estimation of recharge areas in the Región Carbonífera aquifer. Source: own elaboration.

3.2.4. Numerical models

Numerical models are powerful tools are very useful for evaluating most of the components of the hydrological cycle, such as groundwater flow direction and magnitude, effects of extraction rates and managed aquifer recharge, and scenarios of climate variability. However, these require a lot of information and in many cases are difficult to apply, in others, this information is simply not available to the public. For the area of interest, numerical models have been identified for the Texas aquifers, which are described below. In the case of Mexico, the few reports related to the application of numerical models were not accessible; most of these numerical models are not available for public use.

- Carrizo Wilcox: Southern Portion of the Carrizo-Wilcox Aquifer, year 2023. https://www.twdb.texas.gov/groundwater/models/gam/czwx_s/czwx_s.asp
- Edwards (Balcones Fault zone): San Antonio segment of the Edwards (Balcones Fault Zone) Aquifer, year 2004. https://www.twdb.texas.gov/groundwater/models/gam/ebfz_s/ebfz_s.asp

- Edwards-Trinity (Plateau): Edwards and Trinity Regional, conceptual model updated on 2022.
https://www.twdb.texas.gov/groundwater/models/gam/eddt_p/eddt_r.asp
https://www.twdb.texas.gov/groundwater/models/gam/eddt_p/Eddt_Reg_Conceptual_Model_Report.pdf

3.3. Surface water

Information on surface water is crucial to understanding the water availability of an area, the effects of droughts and extreme events, and the effects of water allocation in dams and other reservoirs; it helps in evaluating variables such as groundwater recharge in a water balance model. Surface-water management relies on the scale of analysis and the delimitation of management units known as basins.

3.3.1. Catchment areas and surface water bodies

Most of the hydrological information required to characterize basins and surface water bodies is publicly available for free in both countries. In the case of Mexico, the information on the basins and rivers is distributed between the National Water Information System (SINA) of CONAGUA and the information geo-portals of INEGI. A characteristic to consider is that in Mexico, the basins are divided into Administrative Hydrological Regions (RHA), Hydrological Regions (RH), and management basins (*cuencas de ordenamiento*, in Spanish). The first follows administrative and political limits, while the last two are based mainly on hydrographic limits, sometimes adjusting to political limits.

Basins are the basic units for surface water management in Mexico, in most cases, they are located close to the hydrographic limits; however, more than one management basin is usually required to cover the entire hydrographic basin of a river. The information on basins in the U.S.A is available on the portals of the Texas Water Development Board (TWDB) and The North American Atlas. The former corresponds to basins that cover only Texas, while the latter includes basins that cover the entire U.S.A, Mexico, and Canada. As for Mexico, the U.S.A define administrative limits for water management; however, in the case of basins, the U.S.A tend to consider the hydrographic catchments of a river all the way to its discharge into the ocean, or into the Rio Bravo/Grande; only large catchments are divided into sub-catchments.

Catchments boundaries and major rivers are shown in Figure 14, and the physical properties of the catchments in Table 7. The **local scale** of the data search includes the Rio San Rodrigo, Rio Escondido, Rio Bravo 9 and Rio Bravo 10 catchments on the Mexican side, and portion of the Rio Grande-Falcon catchment on U.S.A side. Most of the basins within the scales of analysis are part of the Rio Grande Basin, a 557,000 km^2 transboundary basin that extends over seven states between Mexico and the U.S.A. In that sense, the use of surface water in the **local scale and intermediate scale** of analysis is subject to the 1944 Treaty between Mexico and the U.S.A, which establishes that Mexico should release a discharge of 432 million m^3/year (average over a treaty cycle of five consecutive years) of water for use in the U.S.A (Sandoval-Solis et al., 2022).

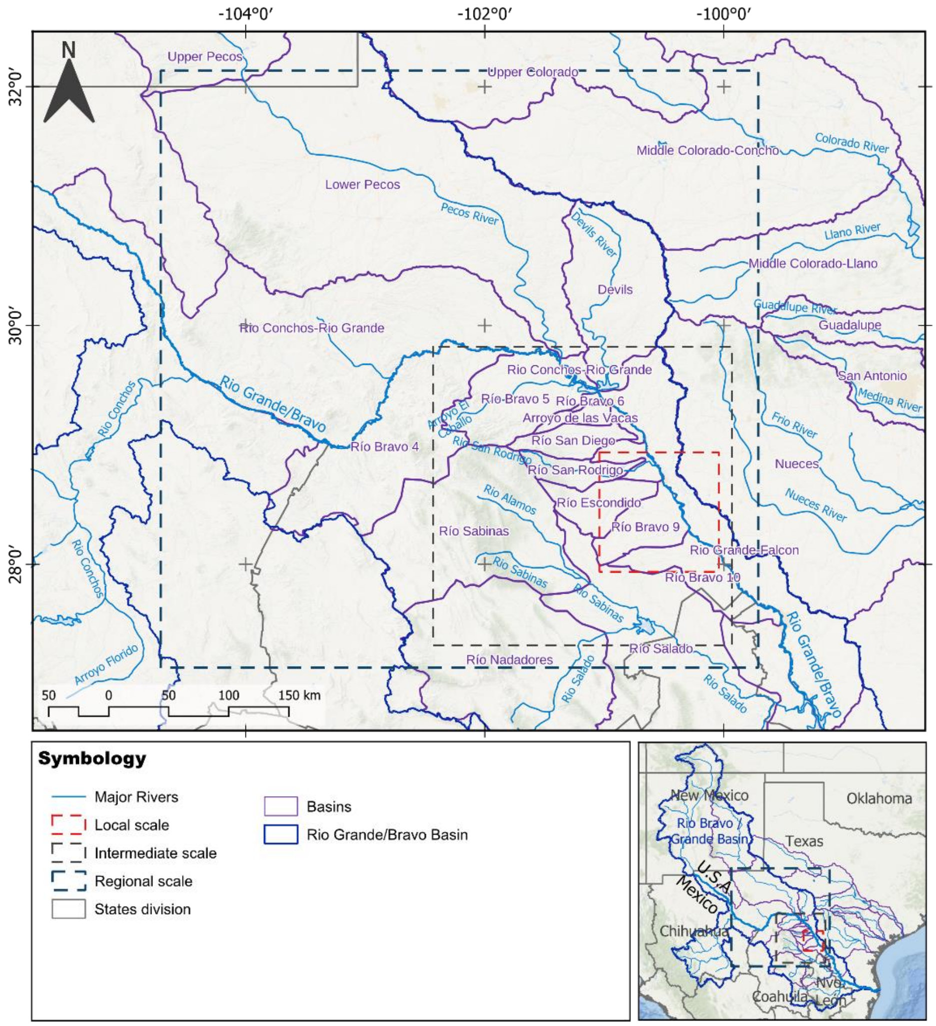


Figure 14. Main basins and rivers in the study area. Source: own elaboration from different data sources.

The catchments that generate runoff in the Colorado, Guadalupe, San Antonio, and Nueces rivers in Texas discharge water to the Gulf of Mexico without having surface interaction with the Rio Grande Basin; therefore, the influence of the activities and water consumption in such catchments may not affect the **local and intermediate scale** of analysis, unless these effects alter the underground flow regime of transboundary aquifers, mainly the Edwards and Edwards-Trinity aquifer.

The catchments located upstream of the intersection of the Río Bravo and the Río Conchos, at the northwest of the area of interest, were not included in the regional scale of this analysis; if the five-year deliveries from the Rio Conchos basin established in the 1944 Treaty are not met, the basins at a regional and local scale (Mexico side) would have to compensate for these water shortages.

On the other hand, the catchments located at a **local scale**, within the limits of the Allende - Piedras Negras aquifer, are headwater catchments and its water availability do not depend on the discharge from upstream catchments.

Table 7. Physical properties of the catchment areas. Source: own elaboration.

Country	Catchment	River	Area	Perimeter	Centroid coordinates		Terrain elevation (m.a.s.l.)		
	Name	Name	(km^2)	(km)	Xc	Yc	Min	Max	Mean
Mexico	Arroyo de las Vacas	Rio Bravo tributary	869	160.355405	-101.213189	29.2256209	273	966	438
Mexico	Río Bravo 10	Rio Bravo tributary	4036	421.552456	-100.185402	27.8890603	111	740	256
Mexico	Río Bravo 4	Rio Bravo tributary	14698	885.88984	-102.846539	28.9844693	356	2723	1081
Mexico	Río Bravo 5	Arroyo El Caballo	6476	418.343765	-101.753933	29.3854591	277	2102	768
Mexico	Río Bravo 6	Rio Bravo tributary	220	81.1138463	-101.127944	29.3657527	268	513	361
Mexico	Río Bravo 7	Rio Bravo tributary	364	137.165473	-100.821048	29.1794415	236	353	292
Mexico	Río Bravo 8	Rio Bravo tributary	1204	232.347135	-100.782013	28.873711	209	478	301
Mexico	Río Bravo 9	Rio Bravo tributary	3057	273.259831	-100.664504	28.3120012	170	691	347
Mexico	Río Escondido	Río Escondido	2880	268.413821	-101.050877	28.5155314	220	1046	466
Mexico	Río Nadadores	Río Nadadores	21748	731.176659	-101.752872	27.1030872	302	3016	1030
Mexico	Río Sabinas	Río Sabinas	17128	626.02963	-102.094541	28.2775447	336	2599	1110
Mexico	Río Salado	Río Salado	23087	950.080412	-100.55181	27.1050562	104	2202	428
Mexico	Río San Diego	Río San Diego	2131	243.01548	-101.266725	29.0359238	257	1514	545
Mexico	Río San Rodrigo	Río San Rodrigo	1912	246.7324	-101.249199	28.7896141	236	1339	563
U.S.A	Devils	Devils River	10884	486.396103	-100.912577	30.3006292	326	827	637
U.S.A	Guadalupe	Guadalupe River	15399	900.946438	-97.9631111	29.5949952	0	739	244
U.S.A	Lower Colorado-La Grange	Colorado River	7528	710.438661	-96.9235185	29.8737214	0	273	113
U.S.A	Lower Pecos	Pecos River	53606	1364.457	-103.037947	31.2152021	320	2609	966
U.S.A	Middle Colorado-Concho	Colorado River	39318	1102.67766	-100.145671	31.4659352	341	904	625
U.S.A	Middle Colorado-Llano	Colorado River	21536	853.320478	-99.0417628	30.4932144	113	760	498
U.S.A	Nueces	Nueces River	43283	1110.68054	-99.2477629	28.7917116	0	740	238

Country	Catchment	River	Area	Perimeter	Centroid coordinates		Terrain elevation (m.a.s.l.)		
	Name	Name	(km^2)	(km)	Xc	Yc	Min	Max	Mean
U.S.A	Rio Conchos-Rio Grande	Rio Bravo tributary	32062	1433.47732	-103.456192	29.9785057	332	2358	1082
U.S.A	Rio Conchos-Rio Grande	Rio Bravo tributary	454	133.222385	-101.217302	29.6290349	328	610	411
U.S.A	Rio Grande-Falcon	Rio Bravo tributary	13283	1063.57476	-99.8348019	28.1148471	57	700	234
U.S.A	San Antonio	San Antonio River	10909	805.360601	-98.3123506	29.3045354	0	725	236
U.S.A	Upper Colorado	Colorado River	41540	1116.31464	-102.15155	32.6343353	515	1377	939
U.S.A	Upper Pecos	Pecos River	61139	1385.27696	-104.721591	33.7756121	867	3976	1525

3.3.2. Streamflow records and surface water availability

Streamflow and runoff data are freely available of charge on the BANDAS webpage from CONAGUA for Mexico, and the USGS National Water Dashboard for the U.S.A. Location of streamflow gauges is shown in Figure 15, as well as the location of major reservoirs and dams within the **regional scale** of analysis. Streamflow records in Mexico are available at hourly and daily timescales; however, there is **a lack of recent streamflow data in the semi-arid and arid regions**. Only three streamflow gauges were obtained for Mexico's catchments (excluding those along the Rio Bravo/Grande), covering periods no longer than 2020; their discharge is for the International Falcon Dam, where the Rio Sabinas catchment overlaps the high-elevation north portion of the Allende-Piedras Negras Aquifer. There is **a lack of streamflow gauges in the Sabinas conglomerate portion of the Allende - Piedras Negras aquifer**, the most exploited portion of the aquifer, which makes it challenging to identify the actual flow and runoff; it becomes difficult to evaluate the availability of surface water at the **local scale**.

More than 40 streamflow gauges were found at the **regional scale**, but records are mainly available for periods later than 1990, as is shown in Figure 16, which visualizes the number of streamflow gauges working simultaneously. As described before, catchments belonging to the Rio Grande may significantly influence the water distribution at the **local and intermediate scales** of analysis; in that sense, most of the available streamflow gages are located along the Pecos River and the Rio Bravo/Grande. Furthermore, within the scales of analysis, streamflow in the Rio Bravo/Grande is regulated by the International La Amistad dam, altering the natural downstream flow.

Monitored rivers on the Mexican side show flow intermittency (percent of time with no flow, i.e., dry conditions) from 15 to 27%, likewise, due to the stronger flow regulations in many U.S.A rivers, intermittency varies from 0% in non-natural flow regimes to 97% in small dry catchments.

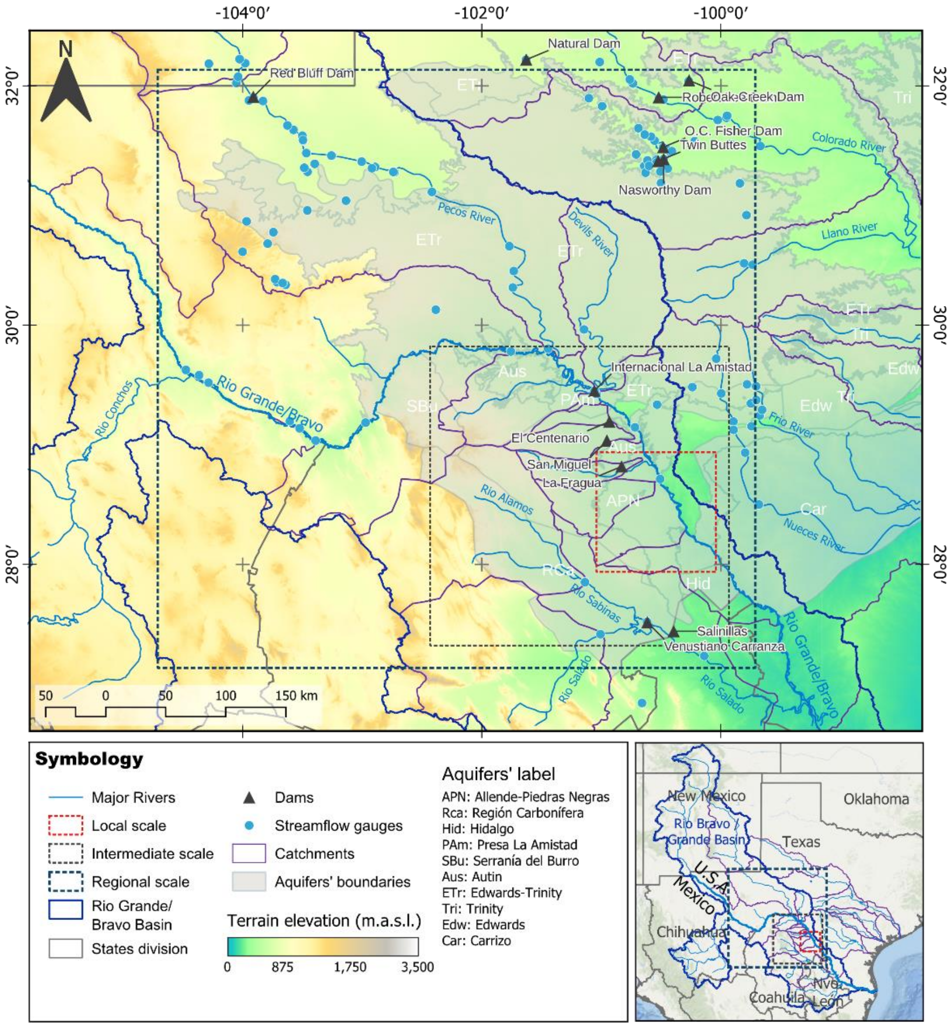


Figure 15. Location of hydrometric stations and main dams in the study area. Source: own elaboration from different data sources.

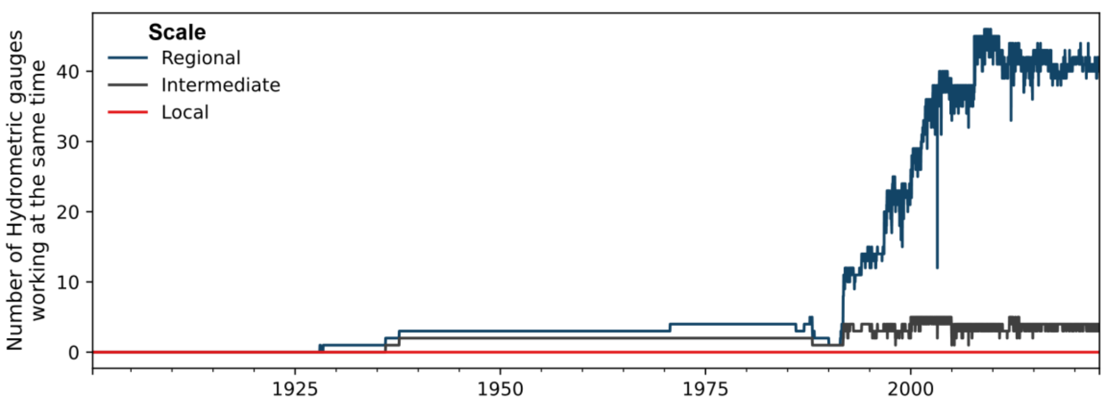


Figure 16. Number of hydrometric stations operating simultaneously at the different analysis scales. Source: own elaboration.

Moreover, the level and storage data in the main reservoirs are available with time series from the operation of each structure, only with some intermittencies in the information. This information is important because the volume of surface water that can be drawn directly from rivers is limited, the dam storage represents the primary source of surface water (in conjunction with the discharge of spring water in some areas). The technical information of the dams can be consulted in Table 8. On a **regional scale**, some dams started operations in 1930, with the La Amistad International Dam having the largest storage volume and crest height. However, even with the large water storage capacity in the dams, it has not been possible to prevent conflicts generated due to drought periods that have complicated the compliance of the Treaty of 1944 and the increase in water consumption, mainly for agriculture (Sandoval-Solis et al., 2022).

Table 8. Properties of the main dams in the study area. Source: own elaboration.

Country	**State**	**Name**	**River**	**Initial operation**	**Crest height (m)**	**Spillway elevation (m.a.s.l.)**	**Capacity (Mm^3)**
Mexico	Nuevo León	Salinillas	Río Salado y Salinas	1930	10	232	19.011
Mex-U.S.A	Coahuila -Texas	Internacional La Amistad	Río Bravo	1968	87.57	340.46	1769.66
Mexico	Coahuila	Venustiano Carranza	Río Salado	1932	38.86	258.87	817.08
Mexico	Coahuila	La Fragua	San Rodrigo	1993	24.7	300.3	47.295
Mexico	Coahuila	El Centenario	Río Manantiales	1935	17	336.15	24.589
Mexico	Coahuila	San Miguel	Río San Diego	1935	15	341.74	21.168
U.S.A	Texas	Twin Buttes	Middle River	1963	41	300.22	1341.4
U.S.A	Texas	Robert Lee Dam		1969	43		999.1
U.S.A	Texas	Red Bluff Dam	Pecos River	1936	32	861.57	640.1
U.S.A	Texas	Oak Creek Dam	Colorado River	1950	29		97.9
U.S.A	Texas	O.C. Fisher Dam	North Concho River	1952	39	590.854	858.9
U.S.A	Texas	Natural Dam		1989	14		255.7
U.S.A	Texas	Nasworthy Dam	South Concho River	1930	14	565.49	52.4

3.4. Groundwater

3.4.1. Groundwater users

The concessions granted for groundwater extraction in Mexico provide an overview of the water balance of an aquifer, which is vital information for managing the resource sustainably.

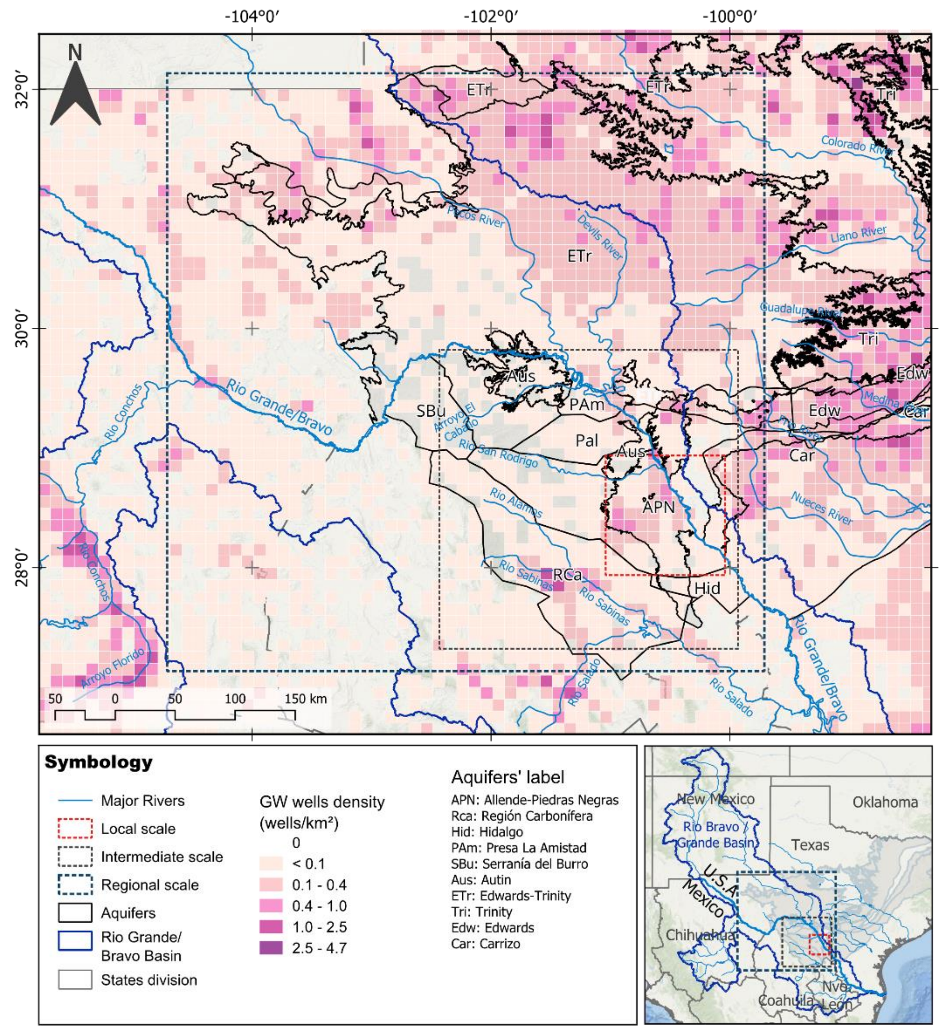


Figure 17. Density of groundwater wells reported until 2020. Source: own elaboration from different data sources.

Groundwater well locations and abstraction values are available in both countries. In the case of Mexico, these data correspond to the Public Registry of Water Rights (REPDA) administered by CONAGUA; while for Texas, they are provided by the TWDB. The density of wells is shown in Figure 17 based on a 5x5 km^2 mesh, where the darker colors correspond to the highest densities of wells. Within the **scales of analysis**, the aquifers with the highest density of exploitation are the north of the Edwards-Trinity aquifer, the Sabinas Reynosa conglomerate in the APN aquifer, and the Region Carbonifera aquifer. The Serranía del Burro, La Amistad, Cerro Colorado, Palestine, and Hidalgo aquifers in Mexico are poorly developed.

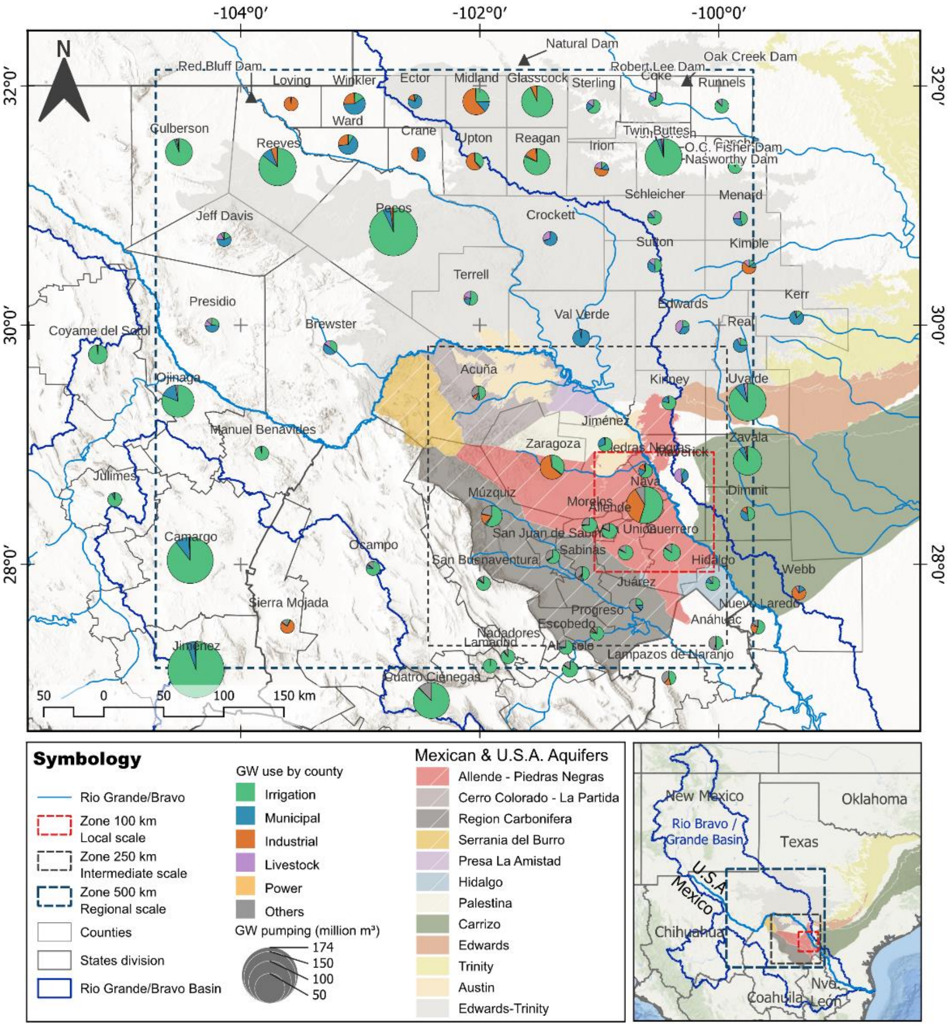


Figure 18. Annual groundwater extraction volumes by county/municipality for the year 2020. The size of the pie charts corresponds to the total extraction volume, and the color proportion of the pie chart corresponds to the main water uses. Source: own elaboration from different data sources.

In Mexico, the REPDA publishes the annual concessioned volume of groundwater, from which it is possible to infer how much water is for different uses, **while in Texas, the TWDB generates annual estimates of groundwater extractions at the county scale**, being available from 2002 to 2020. The map in Figure 18 compares the volume of groundwater extraction for the year 2020 at the municipality/county level, which, for the municipalities in Mexico, was obtained by adding the volume of the REPDA of the uses that fall in each municipality. The most significant groundwater withdrawals are observed in the Pecos, Reeves, Glasscock, Tom Green, and Culberson counties in the Eadwards-Trinity aquifer, with predominant volumes for irrigation. For the Mexican side, larger withdrawals are observed within the Nava and Zaragoza municipalities in the Allende Piedras Negras aquifer, with predominant industrial use.

In 2020, 2,741 concession titles were registered in the REDPA dataset for the Allende-Piedras Negras, Región Carbonífera, Serranía del Burro, Hidalgo, Palestina, and Cerro Colorado-La Partida aquifers. Those concessions include 3,313 wells with 208 Mm^3/year of groundwater withdrawals. At the **intermediate scale**, the primary groundwater uses are for agriculture (59%), followed by industry (25.4%), multiple uses (12.3%), public supply (2.1%), services (0.9%), livestock activities (0.3%), and only 0.03% of groundwater is used for domestic purposes, as shown in Table 9. At the **local scale**, the largest groundwater use is for agriculture and industry (96.2 Mm^3), followed by industrial use (48 Mm^3). The last report in DOF (2023) indicates that groundwater availability is limited, where the Hidalgo exhibited -0.22 Mm^3 of annual groundwater availability, Región Carbonífera showed -27.3 Mm^3, and Allende-Piedras Negras -19.4 Mm^3. However, the methodology implemented for the estimation of the annual groundwater availability has been criticized for many reasons, including lack of recent data for computing the groundwater balance, and for mixing different time scales in the groundwater balance.

Table 9. Groundwater use at intermediate scale. Source: own elaboration using data from REPDA-CONAGUA.

Use	Description	Allende Piedras Negras	Cerro Colorado la Partida	Región Carbonífera	Palestina	Hidalgo	Serranía del Burro
Agriculture	Number of titles	290	2	219	9	9	5
	Number of concessions	489	2	270	14	12	7
	Abstraction (Mm^3/year)	**96.2**	**0.1**	**22.7**	**1.3**	**1.8**	**0.7**
Multiple uses	Number of titles	54	10	65	2	3	0
	Number of concessions	135	10	149	3	17	0
	Abstraction (Mm^3/year)	**14.9**	**0.6**	**9.8**	**0.1**	**0.2**	**0**
Domestic	Number of titles	1	0	19	0	0	0
	Number of concessions	2	0	19	0	0	0
	Abstraction (Mm^3/year)	**0.061**	**0**	**0.009**	**0**	**0**	**0**
Industry	Number of titles	12	0	11	5	0	0

	Number of concessions	42	0	14	7	0	0
	Abstraction (Mm^3/year)	**48.0**	**0**	**4.7**	**0.1**	**0**	**0**
Livestock	Number of titles	53	2	269	3	3	1
	Number of concessions	81	2	324	5	5	1
	Abstraction (Mm^3/year)	**0.2**	**0.014**	**0.4**	**0.009**	**0.019**	**0.004**
Public supply	Number of titles	576	0	762	212	130	0
	Number of concessions	577	0	762	212	133	0
	Abstraction (Mm^3/year)	**2.4**	**0**	**1.3**	**0.6**	**0.2**	**0**
Services	Number of titles	11	0	2	0	1	0
	Number of concessions	16	0	2	0	1	0
	Abstraction (Mm^3/year)	**1.8**	**0**	**0.013**	**0**	**0.005**	**0**
Number of titles		997	14	1347	231	146	6
Total concessions		1342	14	1540	241	168	8
Total abstraction (Mm^3/year)		163.6	0.6	38.8	2.1	2.2	0.7

3.4.2. Water levels, depth to water, water elevation

Groundwater levels are critical to understanding the functioning of aquifers, however, there is a lack of information in time and space to characterize flow patterns, mainly in recent years. In the case of Mexico, these data are obtained mainly from well censuses, which are carried out in the dry season, but these data can be very sporadic. In the case of the United States, there are some automated wells that allow the temporal variation of the groundwater level to be analyzed in greater detail. Figure 19 shows the configuration of the groundwater flow for the Allende - Piedras Negras aquifer for the year 2014, as well as the spring discharge. This information is available mainly for the shallow aquifer, where the groundwater flow is directed towards the Rio Grande. **Additional information is required to identify the direction and magnitude of groundwater flow in deep aquifers, while in other aquifers in Mexico there is not enough information to generate this type of information**.

If that information could be generated, the administratively delimited aquifers could be proven to be part of a larger aquifer system at a larger scale.

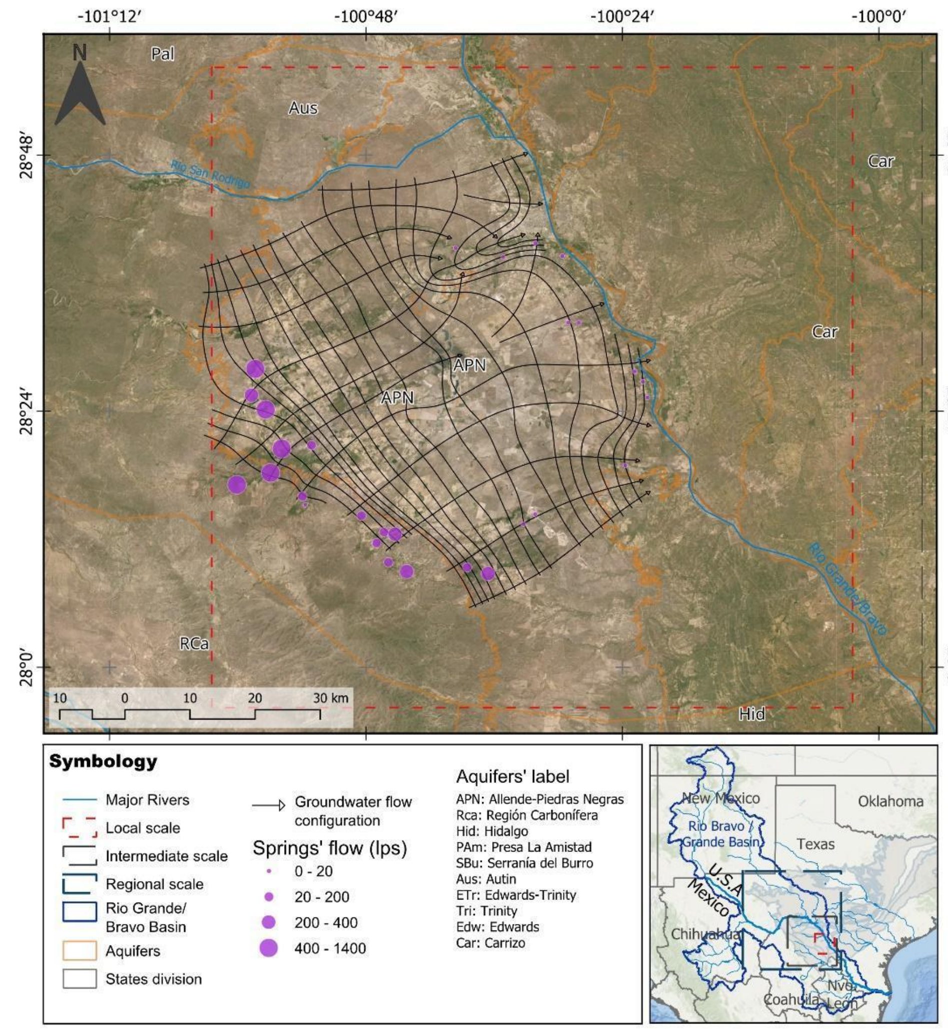


Figure 19. Groundwater flow configuration and springs' discharge at the local scale. Source: own elaboration using data from Lesser y Asociados (2014a) and from SINA-CONAGUA.

3.5. Hydro-geochemistry

3.5.1. Surface water quality

The National Water Quality Measurement Network, also known as RENAMECA, tests and analyzes surface water quality. CONAGUA (2022) uses a color-coded scale to represent water quality. Green is used for compliance with all Mexican regulations, yellow for some non-compliance (Escherichia coli, Fecal Coliforms, Total Suspended Solids), and red for significant non-compliance (mainly Chemical and Biological Oxygen Demand, COD and BOD, respectively).

According to the data obtained from CONAGUA, the sampled surface water bodies demonstrate excellent water quality. The results of these surface water samples are presented in Table 10, which shows that the values of the variables BOD, COD, Escherichia coli, fecal coliforms, and TSS were all below the Mexican regulations, indicating good water quality. Furthermore, Figure 20 provides the sampling points for these parameters.

Acquiring comprehensive information about the physical, chemical, and biological **parameters of surface water is challenging due to the absence of a standardized database of measurement points and timeframes**. Additionally, **several crucial variables that indicate the origins and extent of pollution in the water are not being analyzed**. This includes the identification of the primary sources of pollution, whether they are natural or caused by human activity.

Table 10. Surface water quality at an intermediate scale. Source: SINA – CONAGUA.

		Limits		
Variable	**Average**	**Excellent**	**Good**	**allowable**
BOD (mg/L)	2	<3	3 - 6	6 - 30
COD (mg/L)	10.2	<10	10 - 20	20 - 40
TSS (mg L-1)	12.8	<25	25 - 75	75 - 150
Fecal Coliforms (MPN)	124.8	25	25 - 500	500 - 1000
Escherichia coli (MPN)	75.4	100	100 - 200	200 - 1000

*Most Probable Number methodology

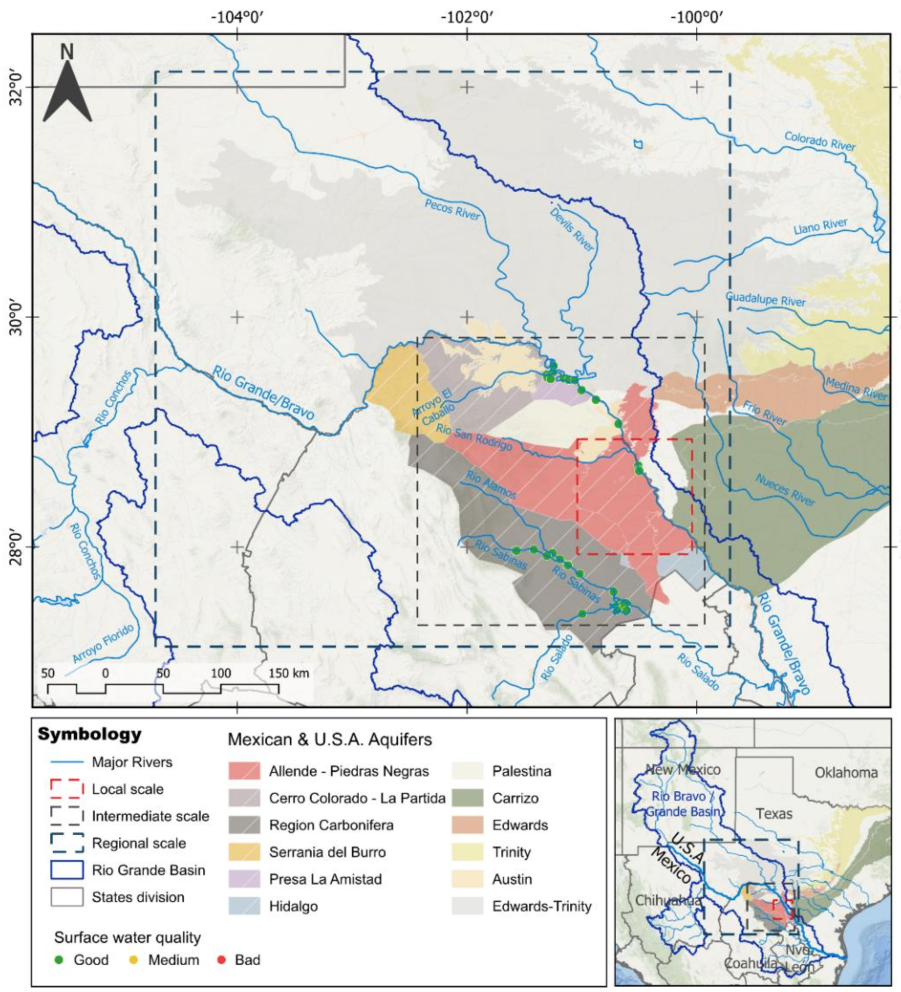


Figure 20. Surface water quality distribution. Source: own elaboration using the RENAMECA dataset and other data sources.

3.5.2. Groundwater quality

Edwards-Trinity Aquifer

Groundwater in Texas and Coahuila is predominantly fresh (TDS < 1000 mg/L). Wells drilled near the "bad water zone" have higher concentrations of up to 2970 mg/L. Samples with low TDS are associated with recharge areas. Samples ranging from 1000 - 3000 mg/L were taken near Nava, Allende, Villa Union, San Carlos, Coahuila, and north of Camp Wood, Texas. They have a distinct chemical character, reflecting different aquifer lithologies and locations within the flow system with respect to recharge and discharge. The presence of the sulfate and chloride ions suggests that the dissolution of evaporite minerals may have contributed to these samples' chemical composition. The likely sources for these minerals are the gypsum and halite sequences in the McKnight and Glen Rose formations (Boghici et al., 2004).

In 2002, TWDB collected groundwater from wells and springs in Val Verde, Edwards, and Kinney counties (TWDB, 2002), these were analyzed for stable and radiogenic isotopes: Deuterium (δ2H), Oxygen-18 (δ18O), tritium (3H), Carbon-14 (14C). Results indicated that the groundwater originated as precipitation and that δ2H and δ18O values have not been altered significantly by water-rock interaction. The data described a trend line with a slope of almost 5, which is typical of evaporative isotope enrichment. This result suggested that the Edwards–Trinity aquifer is dominated by recharge from summer rains, characterized by larger isotope fractionation effects as opposed to winter rains, which is common in arid climates. Moreover, the findings suggest that water loss from a shallow water table may be the predominant evaporation mechanism.

Carrizo-Wilcox aquifer

Groundwater on the Texas side was predominantly fresh to slightly saline with TDS concentrations between 1,000 mg/l and 3,000 mg/l. Salinities in water samples from outcrop wells ranged from 270 mg/l to 1,200 mg/l owing to lithologic heterogeneities in aquifer material and, possibly, reduced recharge rates. The salinity in the Carrizo-Wilcox aquifer increases downgradient as meteoric, fresh recharge dissolves minerals along its flow path and mixes with deep, high-TDS connate water expulsed along fault zones.

The samples are virtually devoid of tritium and exhibit low radiocarbon activities, which is typical for older waters in slow-moving flow systems with very limited active recharge. The very low 14C values are indicative of groundwater that was recharged several thousands of years ago. Highly accurate age estimates based exclusively on carbon isotopes, however, are difficult to derive because of the complex nature of carbon chemistry in groundwater systems. Geochemical processes such as dilution and isotope exchange can strongly alter the initial 14C activity in groundwater, resulting in an artificial aging of groundwaters.

Allende-Piedras Negras Aquifer U.S.A side

Groundwater in both Coahuila and Texas is predominantly fresh to slightly saline, with concentrations between 1,000 mg/L and 3,000 mg/L. Seven wells on the edges of the basin south of Guerrero and one north of Eagle Pass have TDS concentrations ranging from 3,100 mg/L to 30,500 mg/l. Salinities generally increase downgradient as groundwater dissolves aquifer minerals along its flow path towards the Rio Grande and areas of groundwater pumping. Several wells in a north-south trending band between La Compuerta Creek and Nava and between the creeks of Las Cuevas and La Salada, Coahuila were pumping slightly saline groundwater. The predominance of sulfate and calcium ions in slightly saline waters suggests that the dissolution of evaporitic minerals such as gypsum may be one of the chemical processes impacting groundwater quality. The likely source for gypsum is the Lower Cretaceous McKnight Formation of the Maverick Basin, part of the underlying Edwards-Trinity aquifer. Cross-formational flow is the mechanism that mobilizes slightly saline, sulfate-rich water from the McKnight Formation and mixes with the fresh Allende-Piedras Negras groundwater.

The groundwater in the region has a variable level of salinity and sodium content, with variations observed at a spatial level within the aquifer. The eastern region is predominantly dominated by calcium-bicarbonate water, indicating recent infiltration water with short residence periods, having circulated through calcareous sedimentary rocks. In the central-eastern region, calcium-sulfated water is observed locally, which is associated with the presence of gypsum. Moreover, south of Piedras Negras, the water is classified as calcium-mixed, indicating a mixture of water types. The concentrations of iron were recorded to be 3.314 and 0.5641 mg/L in two specific areas, while one sample recorded a Hg concentration of 0.002 mg/L.

Allende Piedras Negras aquifer Mexican side

The concentration of Total Dissolved Solids (TDS) in the aquifer varies from 304 to 2589 mg/L (CONAGUA, 2023). In the western part of the aquifer, TDS concentration is <1000 mg/L, specifically in the Sierra del Burro foothills, west of Zaragoza and Allende. Most of the plain has TDS concentration values between 1000 to 2000 mg/L, while in an elongated strip between Morelos and Zaragoza to the east, water contains TDS concentrations >2000 mg/L. Generally, the central-eastern portion of the aquifer has water with more than 1000 mg/L of TDS. Additionally, the temperature ranges from 19.3 to 36.1 °C, and the pH ranges from 7.1 to 7.6. Occasionally, the concentration of sulfates greater than 400 mg/L is recorded in the vicinity of Zaragoza and Morelos, associated with the dissolution of gypsum and anhydrite from the McKnight Formation.

Región Carbonífera aquifer

The electrical conductivity (EC) values in this aquifer range from <275 to 4000 µS/cm. The valleys of the Álamos and Sabinas rivers, as well as the Sierra de Santa Rosa foothill, have the lowest values, ranging from 300 to 500 µS/cm. In the western part of the aquifer, the region between Múzquiz, Nueva Rosita, Sabinas, Las Esperanzas, and San José de Aura records values of 500 to 1500 µS/cm. However, in the eastern part of the aquifer, towards Juárez-Progreso and the Venustiano Carranza Dam, the water has a higher saline content, with electrical conductivity values between 2000 and 4000 µS/cm. These values are equivalent to salinities between 1600 and 3200 mg/L. Water quality in the Barroterán area and the eastern part of the Progreso-Juárez aquifer is unsuitable for human consumption due to a dangerously high concentration of total dissolved solids (TDS) exceeding 1000 mg/L. However, in Múzquiz, San Juan de Sabinas, Sabinas, Agujita, Cloete, Palau, and Nueva Rosita, the TDS content is within safe limits, ranging between 275 and 620 mg/L. All the analyzed parameters meet the permissible limits according to the Official Mexican Standard, except for the concentration of sulfates in some uses. The sulfate content exceeds 450 mg/L, most likely due to agricultural activities and the presence of evaporitic minerals.

The water in the Sierra de Santa Rosa area is classified as calcium-bicarbonate type due to its contact with the limestone rocks of the mountains and fragments that make up the valleys. In the Region Carbonifera, the groundwater is in the Olmos Formation aquitard and contains gypsum which makes the water belong to the calcium-sulfate family. In the eastern and southern areas of the aquifer, the water has a varied composition due to the presence of evaporitic salts with chlorides and sodium, in addition to the previous components.

Palestina aquifer

The groundwater in the area is mostly of the calcium bicarbonate type, with low salinity levels ranging from 300 to 600 mg/L of TDS. However, there are isolated sites where the concentration can go as high as 2,300 mg/L (DOF, 2015c), which is due to the presence of sulfates from the dissolution of gypsum and anhydrides.

Serranía del Burro aquifer

In this aquifer the concentration of total dissolved solids (TDS) ranges from 296 to 706 ppm (CONAGUA, 2020e).

Cerro Colorado aquifer

The groundwater of the Cerro Colorado-La Partida aquifer is calcium-bicarbonate, with low salinity ranging from 200 to 400 mg/L of TDS (CONAGUA, 2015c).

Hidalgo aquifer

The Hidalgo aquifer's groundwater is composed of sodium-bicarbonate and sodium-chloride. The TDS concentrations range from 2,000 to 8,000 mg/L, according to CONAGUA (2020b). This limits the exploitation of the aquifer since it exceeds the limit for human consumption established in the Official Mexican Standard NOM-127-SSA1-1994. Groundwater with low saline content can only be found in a portion of the aquifer, northwest of the Villa Hidalgo meteorological station, with a TDS concentration of around 1,000 mg/L. To the south of the Colombia meteorological station, the rocks have sodium chloride evaporites, which are easily dissolved by the water that circulates in the subsoil. This has led to several uses with TDS ranging from 2,000 to 6,000 mg/L.

Presa La Amistad

The aquifer's groundwater is typically calcium bicarbonate with low salinity, measuring around 340 mg/L of TDS. However, in some isolated locations, the groundwater has high concentrations of approximately 2,750 mg/L, indicating that it is of the calcium-sulfated type. This is due to the dissolution of gypsum and anhydrite present in the sediments through which the groundwater flows.

In general, **there is a lack of groundwater quality data**, where chemical parameters are measured in a few wells. There is no adequate measurement timeframe that may allow the observation of the evolution of chemical species in terms of their concentration, transport, and fate. Furthermore, **this information is crucial for understanding hydrogeological environments, as it provides information about natural processes and human activities that influence the quality of a water system**. This knowledge is essential for identifying water pollution problems and defining various hydrogeological characteristics, such as recharge, residence times, water origin, and flow systems.

3.6. Environment

3.6.1. Climate and data availability

Climate records and environmental data in the region are essential to evaluate natural water availability, the effects of extreme events (droughts), and the effects of climate change on surface water and groundwater. Many continuous records in time and space are required to assess spatial and temporal climate variability. This is often a problem in many regions due to the lack of information. Still, this problem can be compensated for by including information derived from remote sensors and climate models on a global scale.

The entire region analyzed is located in semi-arid or arid climates, where the energy available to evaporate water is higher than precipitation, leading to high evapotranspiration amounts and low water availability.

The location of available climate stations in the region area is shown in Figure 21; however, **not all stations report information in the same periods, and many others have missing records**, as shown in Figure 22. Climate records are managed and distributed by the Mexican Meteorological Service (SMN) from CONAGUA in Mexico, and the National Oceanic and Atmospheric Administration (NOAA) in the U.S.A Data on precipitation, temperature and evaporation was obtained in both countries at a daily scale, and, in the case of U.S.A, this information was also available at sub-daily scale. Air humidity was only available in the U.S.A Furthermore, climatological stations in Mexico reported values no later than 2020, while most of the climatological stations in the U.S.A report data at the real or near-real time.

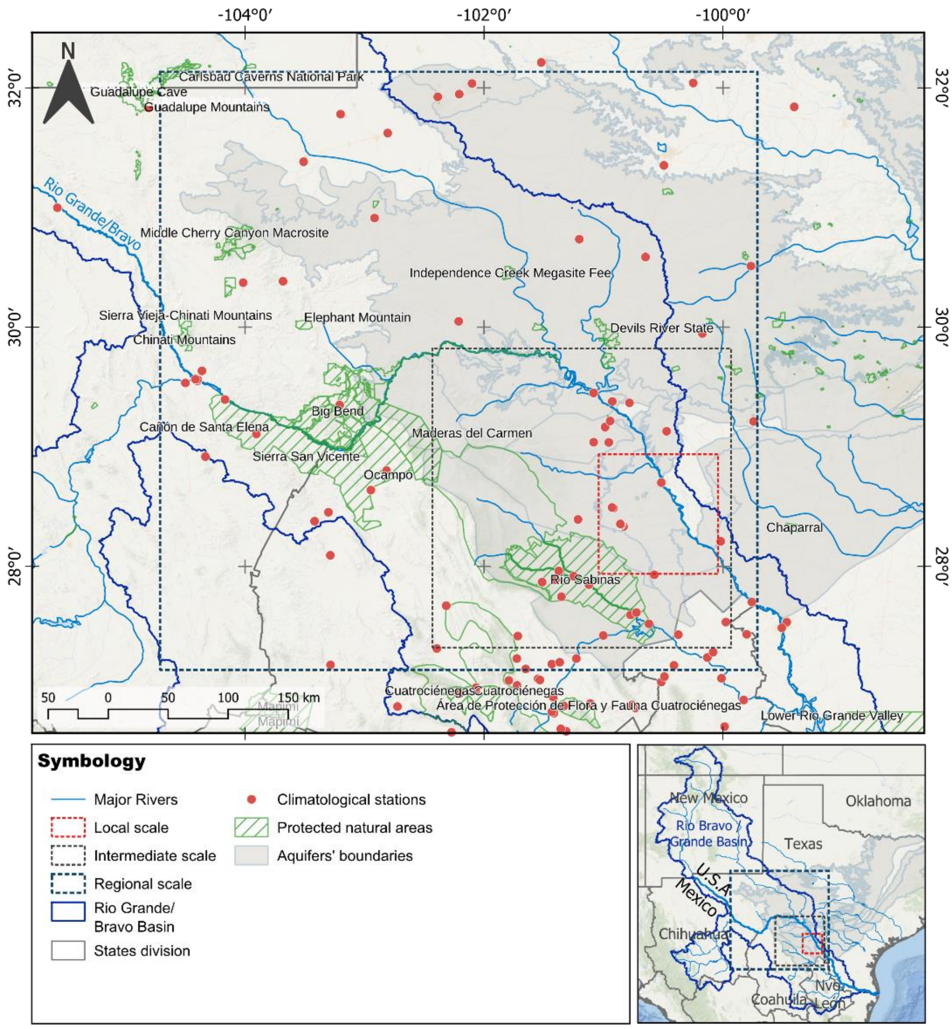


Figure 21. Extension of protected natural areas and location of climatological stations. Source: own elaboration from different data sources.

At the **local scale**, at least seven climate stations were found, but only five use to operate at the same time. Precipitation records are common in comparison with evaporation and relative humidity (Figure 22). The period with the largest number of precipitation and temperature stations working in parallel at the intermediate and regional scales are from 1940 to 2020 and from 1980 to 2020, respectively. Moreover, the number of evaporation records drops to the middle of the precipitation records.

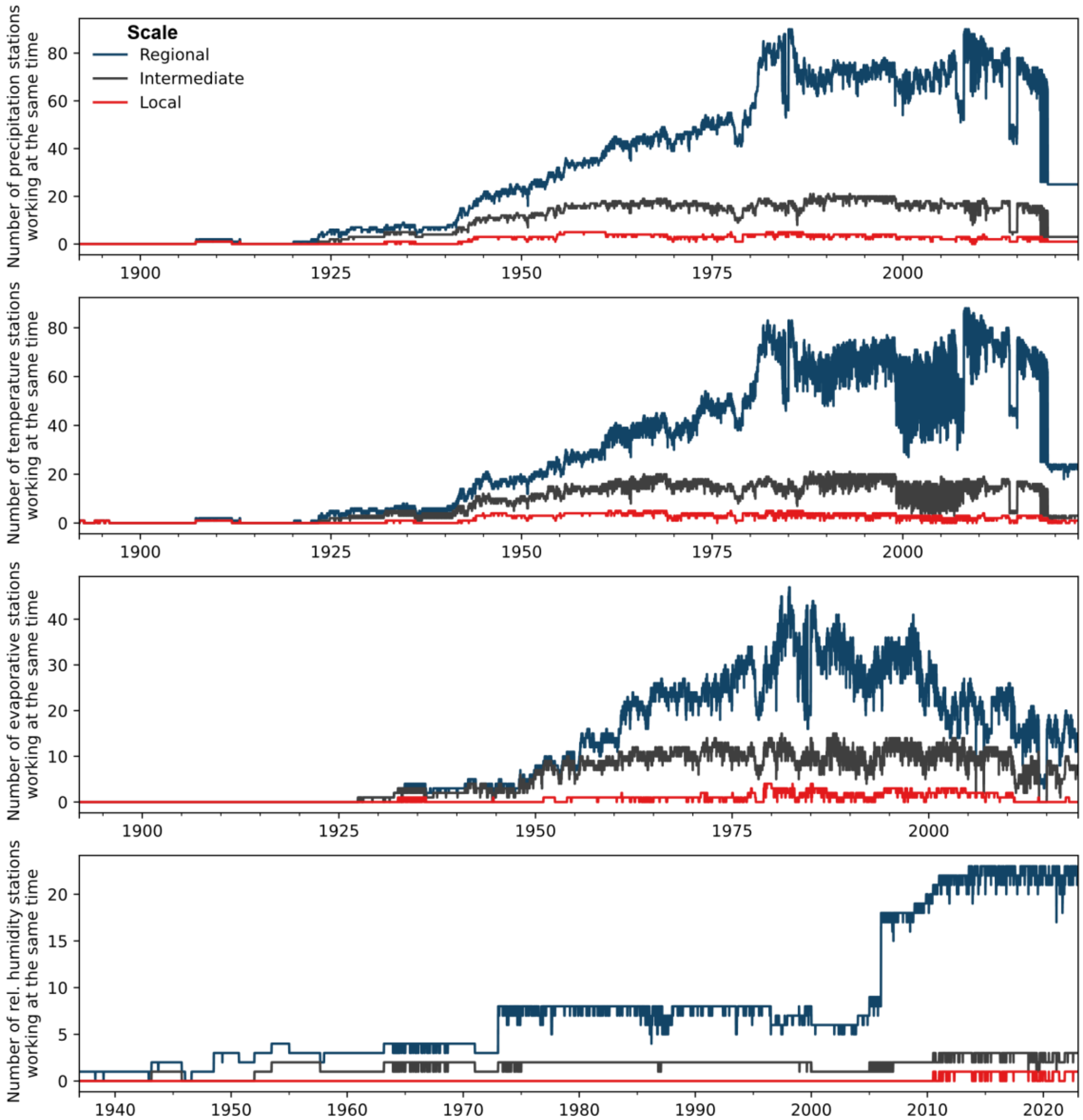


Figure 22. Number of climatological stations operating simultaneously at the different measured variables and analysis scales. Source: own elaboration.

3.6.2. Remote sensing

For the spatial climatological characterization, it is recommended to analyze continuous records in many stations, but **the lack of continuous records represents a challenge in the different scales of analysis**. To address these problems, continuous temporal and spatial data derived from remote sensing and global models is analyzed. Figure 23 shows the mean annual precipitation computed from 1981 to 2022 using the CHIRPS dataset, where it can be observed that lower precipitation amounts are reported to the west of the **regional scale**, with ~200 mm/year, and more than 700 mm/year to the east of the **regional scale**. At the local scale, precipitation ranges from 400 to 480 mm/year, and at **intermediate scale** some regions of higher precipitation (500 to 700 mm) are observed in the higher elevations of the Allende - Piedras Negras aquifer.

Despite higher precipitation rates at the **local and intermediate scales**, these scales also present the highest average daily air temperatures within the scales of analysis, specifically in the Sabinas-Reynosa conglomerate in the Piedras Negras aquifer, exceeding 24 °C according to the NOAA CPC global temperature product. The average air temperature is decreasing below 15 °C towards the northwest of the western part of the Edwards-Trinity aquifer. Extreme temperatures can have substantial repercussions not only on water availability but also on energy consumption for heating and food production. On the other hand, temperature changes can alter evapotranspiration patterns.

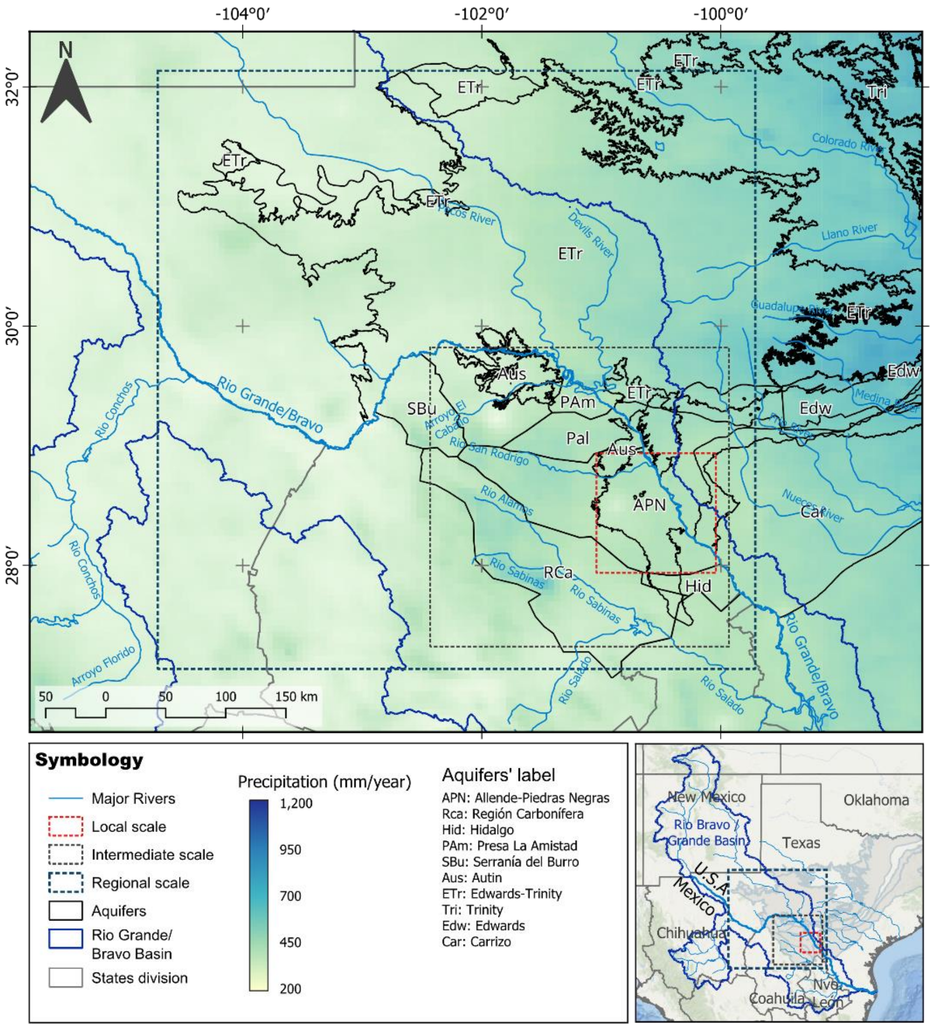


Figure 23. Mean annual precipitation for the period 1981 to 2022 using the CHIRPS dataset. Source: own elaboration.

Mean annual evapotranspiration (ET) from the GLDAS 2.2 is congruent with the temperature (Table 11), where larger ET values (>500 mm/year) are shown in the lowlands of the Allende-Piedras Negras aquifer at the **local and intermediate scales** (Figure 24), representing more than

90% of the mean annual precipitation. High ET values, close to precipitation, are also associated with non-natural soil humidity conditions, which diminishes whit high groundwater withdrawals for crop irrigation. ET decreases below the 300 mm/year at the northwest of the regional scale, but the lower ET/precipitation ration is observed in the Región Carbonífera aquifer.

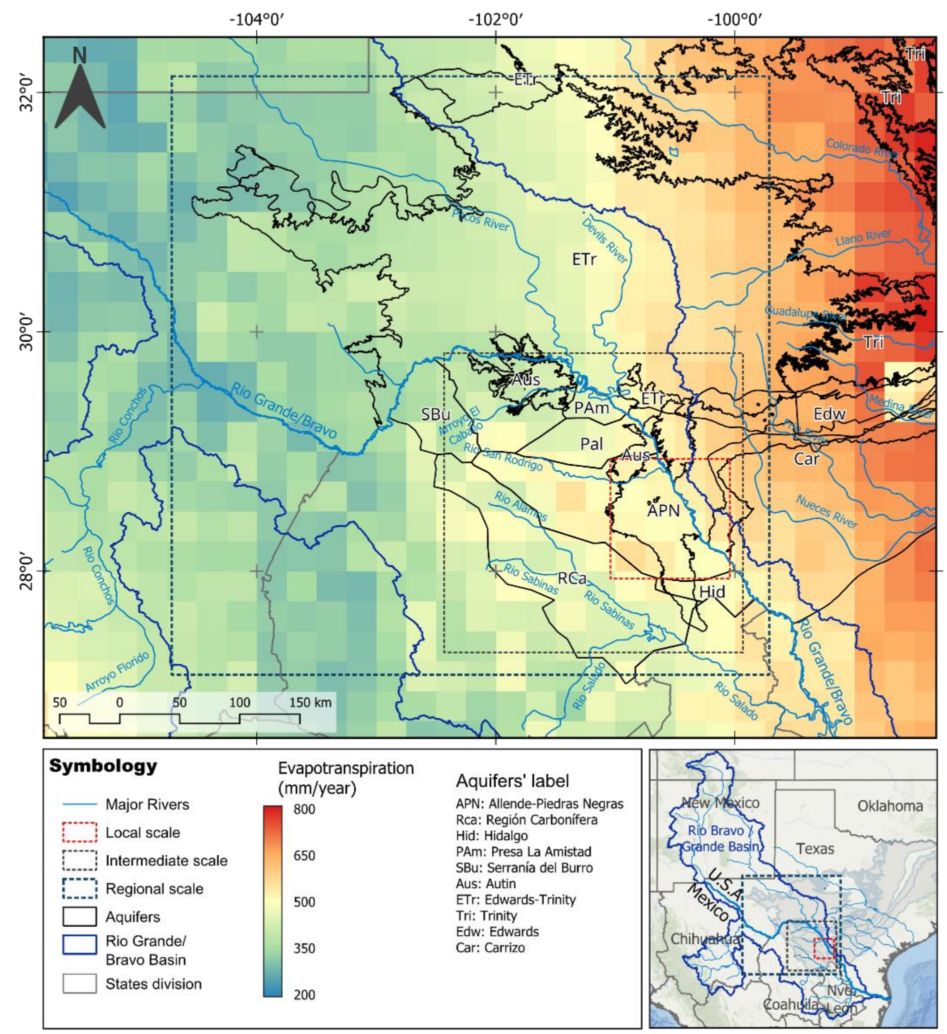


Figure 24. Mean annual actual evapotranspiration for the period 2002-2022 using the GLDAS 2.2 dataset. Source: own elaboration.

Annual and mean monthly climate variability are shown in Figure 25, and a climatological synthesis is shown in Table 11. Except for the Edwards aquifer, the aquifers present similar patterns in precipitation and actual evapotranspiration at the annual and monthly scales. As shown, the APN aquifer has the highest average daily temperature and, in turn, has the highest potential evapotranspiration rates.

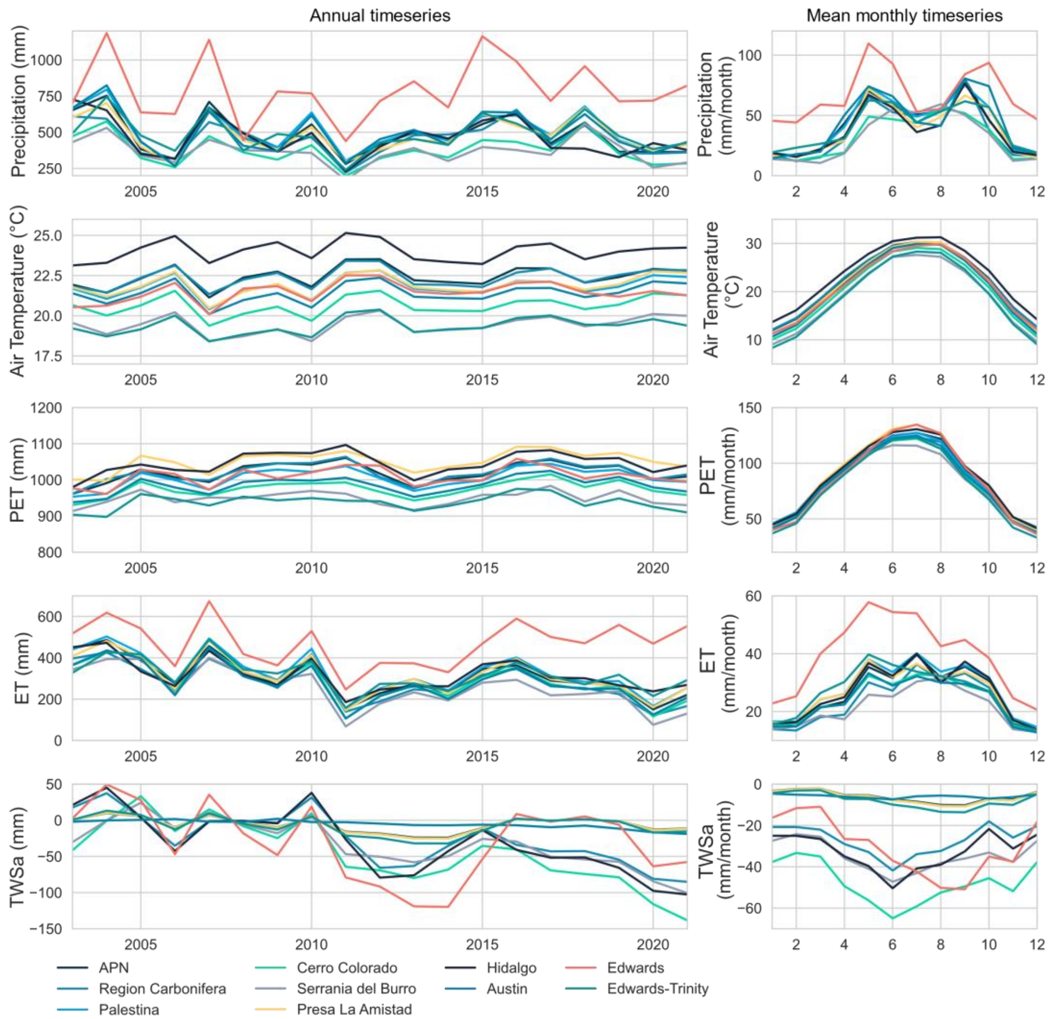


Figure 25. Annual and mean monthly variability of principal hydrological variables. Precipitation was derived from CHIRPS, Air temperature was derived from the NOAA CPC Global Daily Temperature dataset, PET is the potential evapotranspiration derived from the GLD. Source: own elaboration.

The TWSa time series in Figure 25, corresponds to the total water storage anomalies derived from the GRACE NASA Mission, which indicates how water is gained or lost in surface water, soil moisture, and groundwater storage. The APN, Edwards, Cerro Colorado, Serranía del Burro, and Austin aquifers show the most significant fluctuations in terrestrial storage, including negative trends in recent years, which may be associated with the effects of extraordinary droughts, or over pumping. **A deeper analysis of this information could provide an indication on how severe these impacts were for changes in groundwater storage**.

Table 11. Mean annual values of hydrological variables by aquifer. Precipitation was derived from CHIRPS, Air temperature was derived from the NOAA CPC Global Daily Temperature dataset, PET is the potential evapotranspiration derived from the GLDAS 2.2 product, ET is the actual evapotranspiration derived from the GLDAS 2.2 product, and TWSa is the terrestrial water storage anomaly derived from the GRACE product.

Aquifer	Precipitation (mm/year)	PET (mm/year)	AET (mm/year)	AI	SM	Tmin (°C)	Tmean (°C)	Tmax (°C)	TWSa (mm/year)	NDVI
Allende - Piedras Negras	495	1019	309	2.06	0.43	15.7	22.0	28.2	-6.3	0.40
Cerro Colorado	377	975	311	2.58	0.37	13.4	20.3	27.1	-49.8	0.31
Region Carbonifera	448	1020	279	2.28	0.40	15.6	21.9	28.2	-28.2	0.39
Palestina	508	1006	328	1.98	0.43	15.1	21.4	27.7	-6.6	0.39
Hidalgo	450	1046	318	2.32	0.50	17.4	23.4	29.4	-34.0	0.38
Presa La Amistad	461	1051	314	2.28	0.49	15.2	21.5	27.9	-6.6	0.32
Serrania del Burro	376	948	255	2.52	0.36	11.6	19.0	26.5	-36.2	0.28
Carrizo	972	1029	732	1.06	0.54	14.5	20.4	26.4	0.3	0.52
Edwards	802	1010	472	1.26	0.66	15.2	21.2	27.2	-31.3	0.45
Trinity	893	979	619	1.10	0.63	12.8	18.9	25.0	-191.4	0.45
Austin	524	985	281	1.88	0.41	14.5	21.0	27.6	-6.0	0.31
Edwards-Trinity	483	938	318	1.94	0.54	12.0	19.0	25.9	-8.4	0.31

3.6.3. Land use and ownership

Figure 26 shows the land use in the study region, obtained from the USGS North American Land Cover product for the year 2020. Comparison in land use percentages for the years 2010, 2015, and 2020 are shown in Table 12.

Land ownership in both countries has different implications, mainly concerning water use, since article 27 of the Political Constitution of the United Mexican States indicates that water is the property of the Nation and lays the foundations for the State to regulate its sustainable use. Hence, even though landowners may have water stored in lakes, rivers, or aquifers within their properties, they still need permission from the State to be able to extract and use this water.

In the U.S.A., each state regulates the use and extraction of water. In Texas, these regulations are established by the Texas Commission on Environment Quality (TCEQ) in title 30 of the Texas Administrative Code (30 TAC), where it is indicated that surface water is the state's property; therefore, permits are needed for its use. In contrast, groundwater is the landowners' property, so they can extract and use it as required.

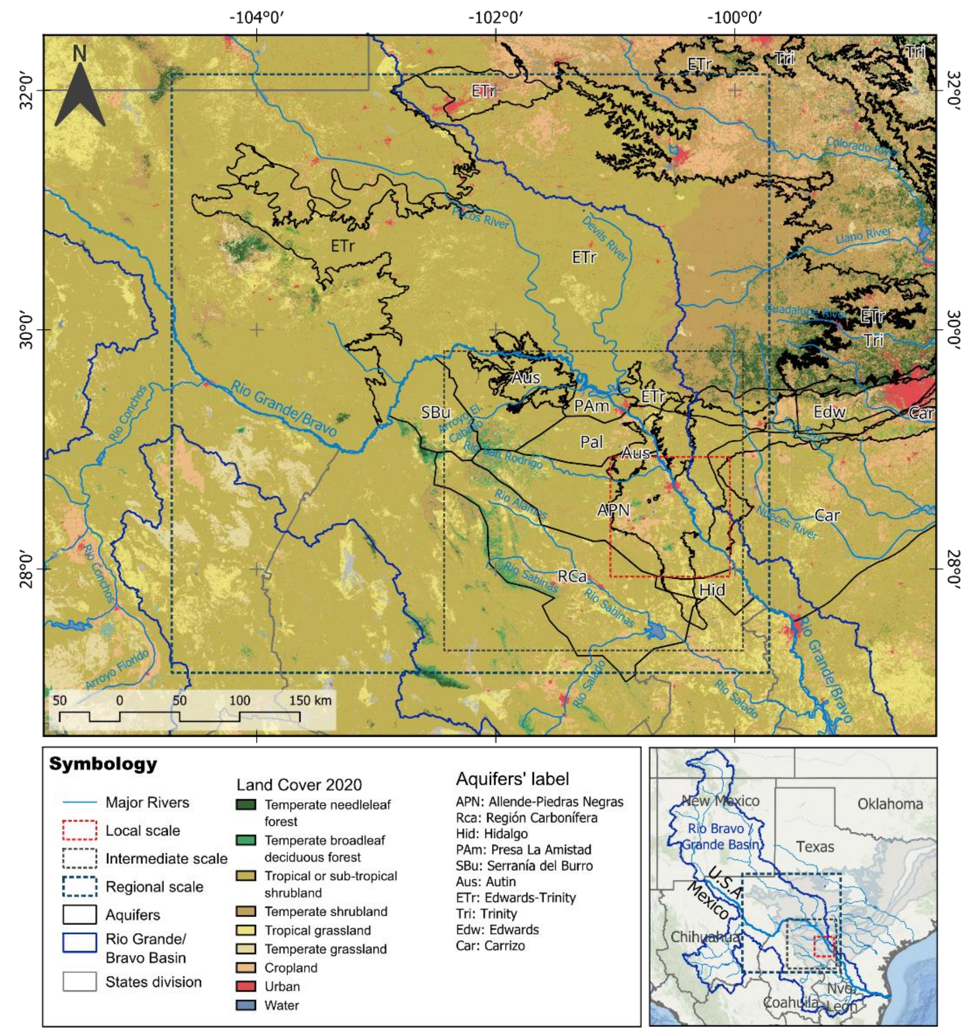


Figure 26. Major land uses for the year 2020 using the USGS North American Land Cover product. Source: own elaboration.

Due to the arid conditions, at the **regional scale**, shrublands are the most abundant cover in all the aquifers analyzed (Figure 26), followed by grassland, and in some high areas, such as the APN, temperate deciduous forest is observed. Moreover, the areas designated for agriculture are representative in the Carrizo-Wilcox, Edwards, APN, and Palestine aquifers; however, a reduction in crop areas is seen in 2020 compared to 2010 in almost all aquifers (Table 12).

There is sufficient environmental information in all the aquifers of interest to examine the climate variability and effects of land use change. This information will be beneficial to analyze climate and anthropogenic impacts, as well as possible groundwater recharge changes in the high areas that contribute to deep regional flow systems, which are very poorly studied in the region.

Table 12. Evolution of land uses (%) by aquifer from 2010 to 2020 using the USGS North American Land Cover product. Source: own elaboration.

Aquifer	Year	Temperate needleleaf forest	Tropical broadleaf evergreen forest	Tropical broadleaf deciduous forest	Temperate broadleaf deciduous forest	Mixed Forest	Tropical shrubland	Temperate shrubland	Tropical grassland	Temperate grassland	Wetland	Cropland	Barren Lands	Urban	Water
Allende - Piedras Negras	2020	0.01	0.02	0.02	2.89	0.01	74.91	1.42	8.75	0.61	0.15	9.18	0.34	1.19	0.49
	2015	0.01	0.00	0.02	2.98	0.00	76.90	1.49	9.69	0.63	0.13	6.20	0.34	1.11	0.51
	2010	0.31	0.00	0.03	2.72	0.00	74.91	1.48	10.74	0.00	0.21	7.55	0.61	1.30	0.13
Region Carbonifera	2020	0.10	0.00	0.00	4.86	0.00	70.32	3.78	11.17	0.75	0.20	6.75	0.19	0.67	1.21
	2015	0.10	0.00	0.00	4.84	0.00	72.76	3.92	12.72	0.78	0.01	2.83	0.21	0.59	1.25
	2010	0.06	0.00	0.03	3.56	0.00	73.38	3.91	14.14	0.03	0.00	3.09	0.01	0.57	1.23
Serrania del Burro	2020	0.77	0.00	0.00	4.59	0.00	79.62	5.48	6.64	0.83	0.03	1.89	0.07	0.04	0.04
	2015	0.77	0.00	0.00	4.57	0.00	79.74	5.57	8.35	0.84	0.00	0.05	0.04	0.04	0.04
	2010	1.04	0.00	0.00	1.43	0.00	75.82	8.92	12.60	0.12	0.00	0.00	0.00	0.04	0.01
Presa La Amistad	2020	0.00	0.00	0.00	0.00	0.00	86.02	0.00	0.72	0.13	0.12	4.01	0.05	3.06	5.88
	2015	0.00	0.00	0.00	0.00	0.00	88.16	0.00	0.74	0.15	0.00	1.51	0.05	2.95	6.43
	2010	0.00	0.00	0.00	0.12	0.00	83.19	0.00	0.23	0.00	0.00	4.71	0.39	3.33	8.03
Hidalgo	2020	0.00	0.00	0.00	0.00	0.00	68.59	0.00	21.78	1.32	0.02	7.84	0.00	0.28	0.16
	2015	0.00	0.00	0.00	0.00	0.00	70.07	0.00	23.47	1.36	0.02	4.60	0.00	0.25	0.22
	2010	0.00	0.00	0.00	0.00	0.00	79.53	0.00	19.30	0.00	0.00	0.79	0.01	0.19	0.19
Palestina	2020	0.02	0.00	0.00	1.12	0.00	85.37	0.03	2.46	0.31	0.09	9.25	0.10	0.51	0.73
	2015	0.02	0.00	0.00	1.13	0.00	88.50	0.04	2.64	0.31	0.01	6.02	0.11	0.46	0.76
	2010	0.39	0.00	0.00	0.51	0.00	86.08	0.04	4.06	0.00	0.01	8.33	0.04	0.29	0.25
Cerro Colorado - La Partida	2020	0.42	0.00	0.00	4.72	0.00	83.39	5.74	2.74	0.79	0.12	1.10	0.20	0.09	0.69
	2015	0.42	0.00	0.00	4.78	0.00	84.13	5.85	2.93	0.80	0.00	0.10	0.21	0.09	0.70
	2010	0.59	0.00	0.00	3.78	0.00	83.43	5.83	5.89	0.05	0.00	0.10	0.19	0.06	0.08
Edwards	2020	13.97	0.84	0.90	1.40	0.59	28.63	16.50	3.06	3.09	0.72	11.92	0.53	17.63	0.22
	2015	12.39	0.78	0.79	3.08	0.45	30.45	17.35	3.25	3.30	0.68	10.17	0.34	16.74	0.22
	2010	12.84	0.90	0.86	3.05	0.06	25.58	14.40	7.20	6.06	0.85	9.27	0.33	18.45	0.17
Edwards-Trinity	2020	3.41	0.18	0.10	0.46	0.03	65.16	23.79	2.24	0.21	0.29	1.86	0.11	1.98	0.18
	2015	3.05	0.17	0.12	0.73	0.02	63.96	23.87	3.99	0.42	0.24	1.47	0.05	1.74	0.17
	2010	3.68	0.26	0.14	1.08	0.01	66.15	22.42	1.66	0.81	0.25	1.24	0.13	1.98	0.20
Austin	2020	0.04	0.04	0.05	0.00	0.04	92.88	0.00	2.93	0.17	0.20	2.76	0.24	0.47	0.18
	2015	0.04	0.04	0.02	0.00	0.01	94.50	0.00	2.97	0.17	0.20	1.15	0.25	0.45	0.19
	2010	0.00	0.05	0.02	0.01	0.00	93.18	0.00	2.59	0.00	0.18	2.58	0.73	0.51	0.15
Carrizo	2020	2.49	7.09	3.59	1.06	9.61	24.86	0.72	3.26	0.47	8.48	30.50	0.22	5.84	1.80
	2015	2.47	6.99	3.71	1.15	9.71	24.86	0.57	3.31	0.68	8.08	30.92	0.28	5.47	1.81
	2010	2.29	5.95	6.51	2.86	5.08	24.83	1.55	5.62	0.50	8.19	27.45	0.59	6.89	1.69

4. DATA GAPS AND RESEARCH NEEDS

The findings, recommendations, and gaps of this research study are set forth below.

Aquifers and groundwater

- At the regional scale, the aquifers are found within three main formations: the Llano uplift, the Ouachita structural belt, and the Balcones fault zone. At the intermediate and local level, two formations - the Taraises and Menchaca - host the aquifers. While there are differences in the way aquifers are delimited between the USA and Mexico, each of them has two hydrogeological units. The shallow aquifers in the United States cover a larger area than those in Mexico. All these aquifers are primarily recharged by precipitation and irrigation return. The Sierra del Burro, The Lomerio Peyotes, and the agriculture areas are the main recharge zones for the Allende-Piedras Negras aquifer. According to its salinity, groundwater is generally of good quality in the northern and western parts at the regional scale. However, it decreases towards the southeastern part, where the APN aquifer is located.
- The basins and sub-basins that interact with the aquifers are largely influenced by the arid and semi-arid climates, summer precipitation regimes, and high temperature and evapotranspiration values. Moreover, the use of groundwater at the **regional scale** is approximately 70% by agriculture, 16% by industry, 5% by public supply, and the remaining 9% is used by rural households.
- There is sufficient geological information to understand each aquifer locally, and efforts have been made to map the extent of transboundary shallow aquifers between Mexico and the U.S.A. However, it is necessary to homogenize the geological information between the two countries to understand the systems and regional groundwater flow rates.
- There are challenges in both countries to standardize the extension of the aquifers, mainly the administrative delimitation in Mexico, which represents a **significant gap** to establishing flow systems at different scales.
- The lack of conceptual models of Mexico's aquifers limits knowing whether they can be affected at intermediate and regional scales. In the case of the APN aquifer, the local flow system is well studied, its degree of interaction between Mexico and the United States is known. Still, more water chemistry information, geophysical studies, and well-logs are required to understand the regional-scale system.
- There is a lack of groundwater level records, which affects the understanding of how pumping and climate may affect groundwater flow. This can be solved using indirect records, but a better understanding of the conceptual hydrogeological model is required.
- More hydro-geochemical information, mainly isotopic records, is required on the Mexican side to improve the understanding of the groundwater flow systems.
- In general, it is necessary to unify the databases of all aquifers in both countries to carry out comprehensive and comparative analyses.
- To accurately determine the quantity and quality of groundwater, a significant amount of information is still needed. The existing information presented in this report is not enough to elucidate two main hypotheses:

1) that the Allende-Piedras Negras aquifer may be considered a truly transboundary aquifer system, and
2) whether the Serranía del Burro, Cerro Colorado-La Partida, and La Amistad aquifers, along with the western part of Allende-Piedras Negras and the northern part of the Region Carbonifera, could be connected to the Edwards-Trinity aquifer, mainly located in the American side of the border.

- Shallow groundwater is understood, deep groundwater is not; this represents a **major gap** in knowledge.
- Deeper layers (limestone) are neither mapped, nor understood; an **important gap** in geological-hydrogeological knowledge.
- The effects of groundwater pumping in the APN (if any) have not been quantified at the intermediate to regional scales.
- At the local, 100-km scale, a more detailed quantitative assessment is needed with local-scale parameters to identify and further refine surface water /groundwater interactions and transboundary groundwater fluxes.
- The resident times of groundwater flow from recharge to discharge areas in the region are not known. The concept of "residence time" is the length of time water spends in the groundwater portion (in an aquifer) of the hydrologic cycle. This can be as short as a few weeks, or as much as 10,000 years or more. It is very useful to determine the residence time of groundwater to evaluate whether it is in steady a state condition (equilibrium) or in transient conditions (disturbed by pumping, geological processes, or changes in climate). This knowledge identifies changes in recharge, discharge, or hydraulic parameters can result in the groundwater system being in disequilibrium which will initiate some transient groundwater behavior. It may also help identify source areas and groundwater flow paths too. Current practices to assess groundwater residence times is with the use of isotopes or calibrated numerical models. There is a clear need for **further research** in this area.
- Very few studies exist on cross-formational flows both in the horizontal and vertical dimensions.
- Limited information on water levels, depth to water, water elevation, and wells at different depths prevents confirmation of the potential hydraulic connectivity between the hydrogeological units, as well as the automated update of piezometric information. This is an important **knowledge gap,** filling this void should confirm, or reject, the hypothesis that the administratively-delimited aquifers in Mexico are part of a larger regional-scale aquifer system.
- At the intermediate scale, there is information from CONAGUA on major and trace elements, as well as some organic compounds present in the water, mainly for the Allende-Piedras Negras and Region Carbonifera aquifers. These chemical parameters are measured in a few wells. However, there is not an adequate measurement timeframe that would allow observing the evolution of these chemical species in terms of their concentration, transport, and fate. Furthermore, this information is crucial for understanding hydrogeological environments, as it provides information about natural processes and human activities that influence the quality of a water system. Filling this **knowledge gap** is essential for identifying water pollution problems and defining various hydrogeological characteristics,

such as recharge, residence times, water origin, and flow systems. **Further research** is needed in this area.

- Further in-depth studies are required including hydrogeological, hydrogeochemical, and environmental aspects to create conceptual and numerical models for the ensemble of aquifer systems to the three extents as described above. This could only be achieved by coordinating efforts between different administrative jurisdictions on both sides of the border.
- The data and information presented in this report represent the first real effort to integrate existing information at the three scales, in a systematic manner. Further works are needed to understand and compare the relative situation of each aquifer, and their hydraulic connection, if any, not only for the natural environment of the aquifers, but for the socioeconomic, administrative, and legal issues in each geographical zone included in this study; these form the bases of other deliverables, D1.3, D1.4, D1.5, and D4.1.

Watersheds and surface water

- Surface water information is sufficiently available to understand seasonal flow patterns. However, for the local scale, the lack of natural flow data, which is not affected by dam storage, complicates its use to understand surface water and groundwater interaction processes. This **data gap** could complicate the development application of numerical models, mainly to adequately represent surface flows and how they interact and may affect groundwater flow systems.
- At the local scale, there is an evident lack of streamflow gauges, making it difficult to determine the actual flow and availability of surface water; long time series of runoff to analyze surface water availability are limited. Yet, a large amount of spatial and temporal information is required to analyze patterns and changes over time, evaluate the interaction of surface water and groundwater, and recognize if there is a decrease in surface water that could mean a greater dependence on groundwater in the future.

Environment

- There is sufficient environmental information in all the aquifers located in the study region to examine the climate variability and effects of land use change. This information will be beneficial to analyze climate and anthropogenic impacts, as well possible groundwater recharge changes in the high areas that contribute to deep regional flow systems, which are very poorly studied in the region.
- At the intermediate and regional scales, it is often a problem to fully assess climate variability and its effects on water resources due to the lack of information. Nowadays, this problem can be compensated for by including information derived from remote sensors, or satellite imagery, such as GRACE, NDVI, SAVI, InSAR. **Further research** is needed in this area.