

## Chapter 4

# Hydrogeology of Edwards–Trinity Aquifer of Texas and Coahuila in the Border Region

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### Introduction

Since 1994, and in cooperation with the U. S. Environmental Protection Agency, the Mexican and American Sections of the International Boundary and Water Commission, and Comision Nacional del Agua, the Texas Water Development Board (TWDB) has been working to (1) identify and characterize the groundwater resources shared by Mexico and the United States along their transboundary extent; (2) to identify any environmental and water-quality problems in the aquifers; and (3) to collate binational data into one geographic information system (GIS) database. This work has resulted in the delineation and characterization of several binational aquifers (Hibbs and others, 1997; Boghici, 2002). One of the binational aquifers delineated and characterized was the Edwards–Trinity aquifer. The states of Texas and Coahuila share the water resources of this carbonate aquifer that spans the international border. This paper presents the results of hydraulic-head mapping, describes the quality of groundwater and the mechanisms of aquifer recharge and discharge, and estimates the recoverable quantities of groundwater.

### Location and Extent

The segment of the Edwards–Trinity aquifer discussed in this paper underlies an area of 31,050 km<sup>2</sup>, of which 16,000 km<sup>2</sup> are located in Mexico. The limits of the study region at the northeast, northwest, and southwest are also the aquifer limits (Figure 4-1). The eastern boundary of the system in the study region is the "bad-water line", or the line of 1,000 mg/l line of total dissolved solids (TDS) concentration (Maclay and others, 1980). The bad water line has been traced south into Mexico and bounds the aquifer system to the east of Serranía del Burro and Peyotes anticline in Mexico (Lesser and Lesser, 1988).

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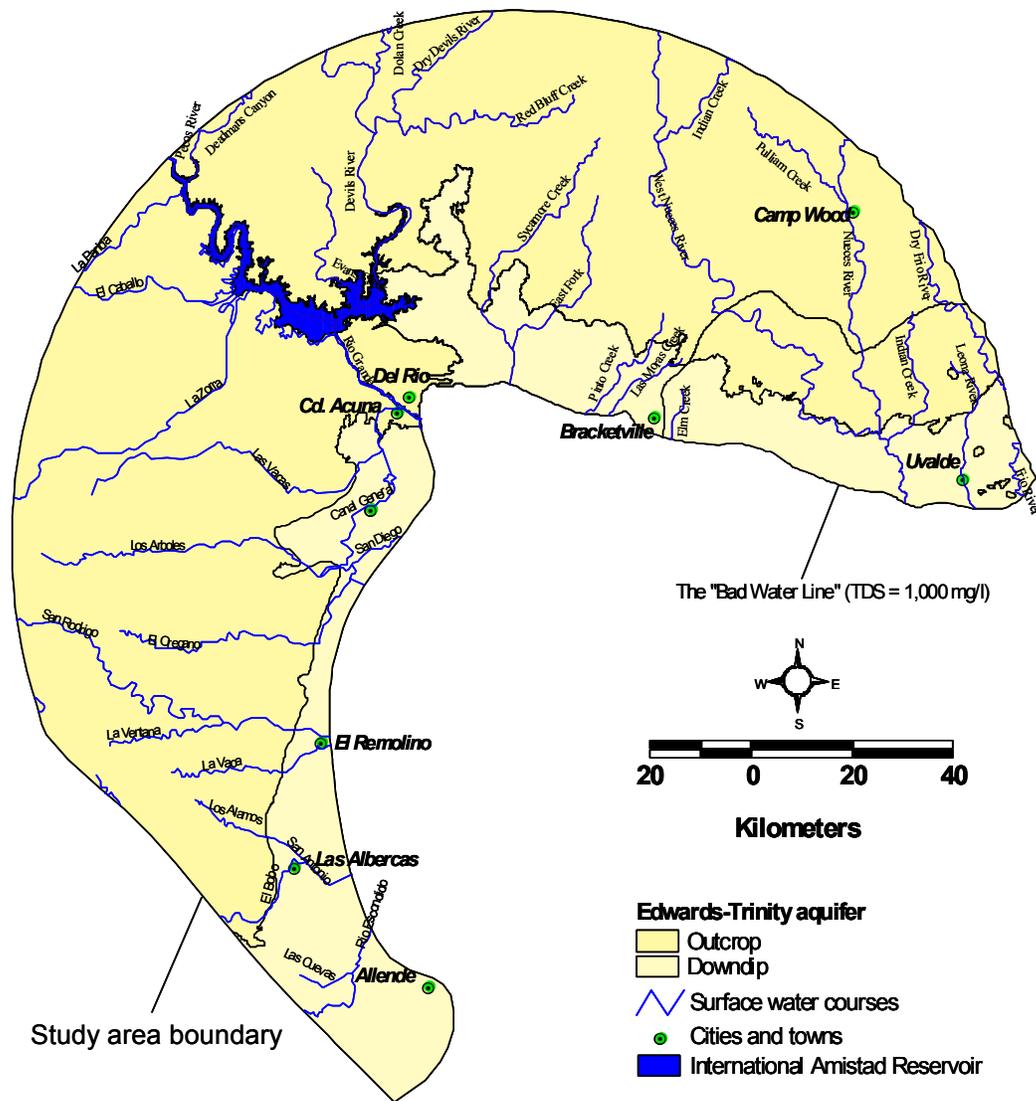


Figure 4-1: Location of the Edwards–Trinity aquifer

## Stratigraphy and structure

The lithostratigraphic and regional hydrogeologic units in the study area are summarized in Figure 4-2. The Edwards–Trinity aquifer system is hosted by lower Cretaceous rocks (Trinity, Fredericksburg, and lower Washita groups) that cover low-permeability and structurally complex pre-Cretaceous rocks. They are overlain by the semi-permeable upper Cretaceous rocks (upper Washita through Navarro groups), which are locally regarded as confining units (Barker and others, 1994). In northern Coahuila, Mexico, the Cretaceous System is divided into three series. These are the Coahuilan, Comanchean, and Gulfian. In southwestern Texas the Cretaceous System includes the Comanchean and Gulfian Series.

ERATHEM	SYSTEM	SERIES	GROUP	UNITED STATES		MEXICO		
				DEVILS RIVER TREND	MAVERICK BASIN			
CENOZOIC	Quaternary			Alluvium				
	Tertiary			Uvalde Gravel	Sabinas Conglomerate			
MESOZOIC	CRETACEOUS	GULFIAN		Anacacho Limestone	Taylor & Navarro Groups			
					Austin Group			
					Eagle Ford Group			
					Buda Limestone			
					Del Rio Clay			
		COMANCHEAN	Washita Group	Devils River Formation	Salmon Peak Formation			
			Fredericksburg Group		McKnight Formation			
			Trinity Group		West Nueces Formation			
		PERMIAN	Cambrian through Pennsylvanian			Maxon Sand		
						Basal Cretaceous Sand	Glen Rose Limestone	
Pearsall Fm.	La Pena Formation							
Sligo Fm.	Cupido Formation							
				Hosston Formation				
PALEOZOIC	PERMIAN			Undivided				
	Cambrian through Pennsylvanian			Rocks of Ouachita Structural Belt				

EXPLANATION

- Allende - Piedras Negras Valley aquifer
  - Cretaceous rocks not part of Edwards-Trinity aquifer system because they are discontinuous, unsaturated, or have low permeability
  - Edwards-Trinity aquifer system
- Modified from Barker et al., 1994, table 1

Figure 4-2: Correlation diagram showing geologic and hydrogeologic units in the Edwards–Trinity aquifer system, Texas and Coahuila.

The Comanchean in Texas begins with rocks of the Trinity Group, which includes the Hosston, Sligo, and Pearsall formations; the Glen Rose Limestone; and the Maxon Sand. The terrigenous Hosston Formation, consisting of siltstone and sandstone, is up to 270 m thick (Imley, 1945). The overlying limestones, dolostones, and evaporites of the Sligo Formation are up to 70 m thick (Bebout and others, 1981). The Pearsall Formation is up to 130 m thick (Barker and others, 1994) and includes strata above the Sligo Formation and below the Glen Rose Limestone.

Three Pearsall members have been recognized in the Balcones Fault Zone area, corresponding to the counties of Kinney and Uvalde in the study region:

- The Hammett Shale, composed of clay, silt, lime mud, and silt-sized dolomite;
- The Cow Creek Limestone, represented by fine- to coarse-grained calcarenite, and beach deposits; and
- The Hensel Sand, which comprises a mixture of limey sand, shale, chert and dolomite pebbles that typically form a basal conglomerate.

The Glen Rose Limestone is a fossiliferous, sandy limestone alternating with calcareous marl, shale, and clay, with laterally continuous beds of gypsum and anhydrite. Its thickness under the study area can reach 460 m (Welder and Reeves, 1962). In western Val Verde County, the Glen Rose Limestone is overlain by the Maxon Sand, which is a medium-to-coarse sandstone, alternating with conglomerate, limestone, and mudstone (Butterworth, 1970).

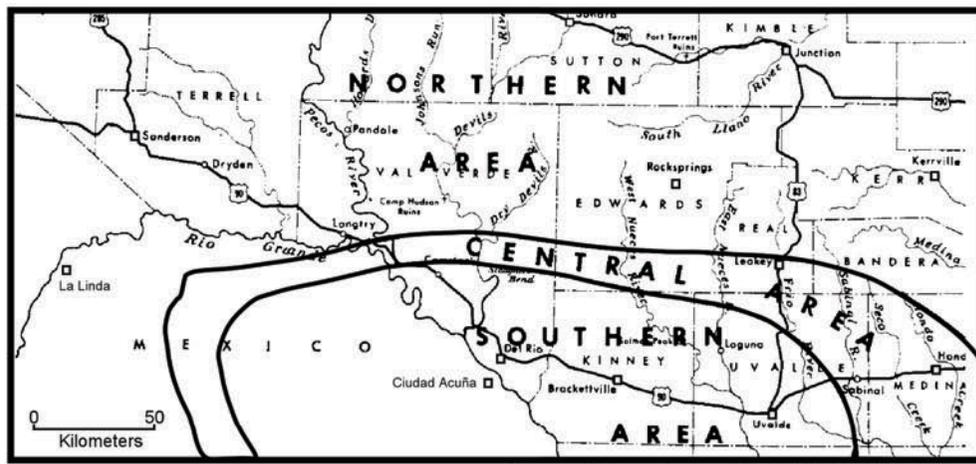
In northern Coahuila the Cretaceous begins with the Coahuilan Series, where Smith (1970) mapped two formations: La Mula and Cupido. The La Mula Formation is predominantly a red silty shale interbedded with lime mudstone. In the study area, wells have intercepted about 75 m of La Mula material, which can get as thick as 760 m in the south (Smith, 1970). At the top of La Mula Formation rest the marine limestone and shale of the Cupido Formation. The Cupido is 160 to 275 m thick (Smith, 1970) and is equivalent to the Hosston and Sligo formations described in Texas (Loucks, 1977).

The Trinity Group in the subsurface of northern Coahuila, Mexico, is comprised of La Pena Formation and the overlying Glen Rose Formation. The 60-m thick La Pena beds consist of black shales and mudstones and are equivalent to the Pearsall Formation in Texas (Smith, 1970). The Glen Rose Formation in northern Coahuila is exposed in Serranía del Burro and is similar to the Glen Rose Formation of Texas.

The Fredericksburg and Washita Groups are genetically related rock formations that unconformably rest atop the Trinity Group. Lozo and Smith (1964) divided the area occupied by the Fredericksburg and Lower Washita groups into three geologically distinct regions: northern, central, and southern (Figure 4-3).

The Upper Washita, represented by the Del Rio and Buda beds, overlies all three regions. In the northern region, the Fredericksburg and Lower Washita Groups consist of rocks of the Fort Terrett and Fort Lancaster formations. The Fort Terrett Formation is at most 100-m thick (Rose, 1972) and is made of limestone with dolomitic and gypsiferous intercalations. The Fort Lancaster Formation is a thick-bedded, rudist-bearing limestone, with a maximum thickness of 120 m (Barker and others, 1994).

In the central region, the Fort Terrett and Fort Lancaster formations grade into a narrow, oval carbonate bank that is known as the Devils River Trend (Figure 4-3). The Devils River Trend is stratigraphically represented by the Devils River Formation, a 210-m-thick pack of fossiliferous limestone, and reef debris (Lozo and Smith, 1964).



Map modified from Lozo and Smith (1964) and Smith (1970)

Figure 4-3: Distribution of geologic province areas within the Fredericksburg and Washita groups in Texas and northern Coahuila, Mexico (modified from Lozo and Smith, 1964; and Smith, 1970).

The Devils River Trend wraps around the Maverick Basin at the west and northwest, and the Stuart City Reef bounds the basin to the south. The Fredericksburg and Lower Washita units of the Maverick Basin are the West Nueces, McKnight, and Salmon Peak formations. The West Nueces Formation can reach 80 m in thickness and consists of nodular, fossiliferous limestone closely resembling the Fort Terrett and Devils River formations (Smith, 1979). The McKnight Formation incorporates about 90 m of thin-bedded carbonate mudstone, petroliferous shale, and evaporitic deposits (Maclay and Small, 1983). The 160 m-thick Salmon Peak Formation (Humphreys, 1984) concludes the Lower Washita succession with a dense, thick-bedded, mudstone that grades upward into a cross-bedded, fossiliferous grainstone (Smith, 1979).

The terrigenous Del Rio Clay blankets the Salmon Peak, Devils River, and Fort Lancaster formations in the study area. The unit is about 50-m thick near the city of Del Rio, Texas, and thins radially away from Del Rio. The Del Rio Clay consists of interbedded calcareous and siliceous flagstones and marly limestone (Adkins, 1933). The Buda Limestone is about 30-m thick in the study region, covers the Del Rio Clay, and consists of limestone with marly interbeds (Rose, 1972).

The Upper Washita strata are overlain in parts of Kinney and Uvalde counties by rocks of the Eagle Ford, Austin, Taylor, and Navarro groups belonging to Gulfian Series. The Eagle Ford–Navarro sequence consists mainly of interbedded shale, siltstone, limestone, chalk, and marl (Bureau of Economic Geology, 1983) and serves locally as the confining unit for the westernmost segment of the Edwards (Balcones Fault Zone) aquifer.

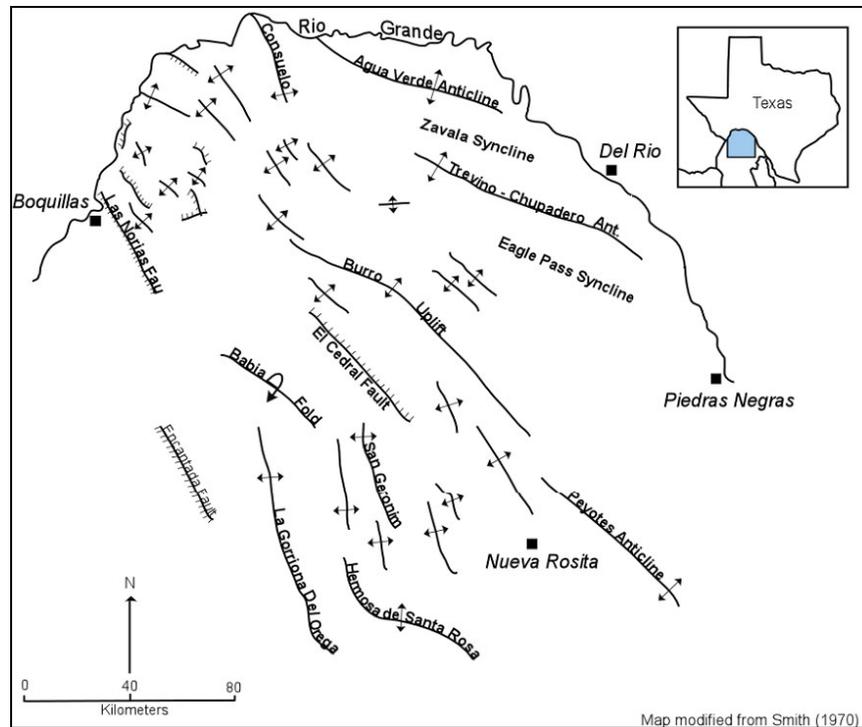


Figure 4-4: Principal structural features of northern Coahuila, Mexico.

The main structural feature in Northern Coahuila was produced during the Laramide Orogeny (late Cretaceous-middle Tertiary time) and consists of an elongated anticline (the Burro Uplift) running northwest to southeast, topographically expressed as the mountains of Serranía del Burro and Lomerio de Peyotes (Figure 4-4). This upwarp is folded into several smaller synclines and anticlines with axes paralleling the main structure, namely the Agua Verde Anticline, the Zavala Syncline, the Treviño–Chupadero Anticline, and the Eagle Pass Syncline (Figure 4-4). Normal faults trending northwest to southeast and believed to have developed after the folding episodes, are also common in northern Serranía el Burro (Smith, 1970).

Barker and Ardis (1992) have addressed the relationship between the regional structure and the Paleozoic topography and their impact upon the thickness of the Cretaceous strata. According to them, the Paleozoic depositional surface “was considerably flatter than the present-day base” which now shows the combined effects of subsidence, uplift, folding, faulting, and structural collapse caused by mineral dissolution.

The configuration of the Edwards–Trinity aquifer bedding is, for the most part, the result of the Cretaceous overburden adjusting to the topography of its Paleozoic base (Barker and Ardis, 1991). The elevation of the Edwards–Trinity aquifer base in the study area ranges from over 1,500 m below sea level in southern Medina County to over 400 m above sea level in northern Val Verde County (Barker, 1996). No pre-Cretaceous

structural information was available for the Mexican side of the study area at the time this paper was being written. Under Val Verde County, the aquifer base is sloping towards the south-southwest at an average rate of 10 m/km, but displays a steeper section (up to 12 m/km) in the northwestern part of the county. Under Edwards and Real counties, the Paleozoic base is flatter (8 m/km) and trends toward the south, where it becomes much steeper under southern Uvalde County (61 m/km). This considerable plunge of the base coincides geographically with the western end of the Balcones Fault Zone and was caused by subsidence towards the ancestral Gulf of Mexico and by fault displacements atop the Ouachita structural belt (Flawn and others, 1961).

## **Water-bearing characteristics**

Rocks of the Trinity, Fredericksburg, and Washita groups host the Edwards–Trinity aquifer, which, in the study area, is composed of two aquifers and the associated confining units. The aquifers are named the Edwards (Balcones Fault Zone) in the Balcones Fault Zone and the Edwards–Trinity (Plateau) in the Edwards Plateau. Due to their hydraulic interconnectedness (Barker and others, 1994), these individual aquifers will be discussed together and referred to as the Edwards–Trinity aquifer throughout this paper.

The Edwards–Trinity aquifer is predominantly made of limestone and dolomite in its upper part and sand in its lower part. The aquifer includes all the Trinity and Fredericksburg strata plus all the Washita rocks below the Del Rio Clay or Buda Limestone (where the Del Rio is missing) or land surface.

### **Trinity Group**

The lowermost Edwards–Trinity hydrogeologic units belong to the Trinity Group. Few water wells are deep enough to penetrate Trinity rocks in the study area. Therefore, the transmissive properties of these strata remain largely unknown.

In Val Verde County, the Hosston and Sligo formations are thin and contain small quantities of saline water whereas the Glen Rose Limestone yields very small to moderate amounts of brackish water (Reeves and Small, 1973). The Hosston and Sligo formations under Kinney County are not tapped by water wells: According to Bennett and Sayre (1962): “They [Hosston and Sligo formations] probably contain water, but the quality is unknown”. In Kinney County, neither the Pearsall Formation nor the Glen Rose Limestone are known to yield water to wells. Bennett and Sayre (1962) estimated that the Glen Rose Limestone might contain small amounts of moderately to highly saline (TDS > 3,000 mg/l) water. In Edwards County, the Basal Cretaceous Sands are water bearing and yield brackish groundwater (TDS > 1,000 mg/l) to four wells. The Hosston and Sligo formations in Uvalde County were encountered in several deep wells. The TWDB groundwater database lists only one Uvalde County well producing 1,000 mg/l TDS groundwater from the Hosston formation. The Upper Member of the Glen Rose Limestone is generally interpreted to be a confining unit (Clark and Small, 1997). Several

Uvalde County wells screened in the Glen Rose evaporitic sections are known to yield brackish (TDS > 1,000 mg/l) groundwater to wells.

The La Mula and Cupido formations are the Mexican equivalents for the Hosston and Sligo formations of Texas. Leal (1992) classifies the La Mula–Cupido as an aquifer, although its importance seems to be restricted to the area south of Serranía del Burro. Leal (1992) indicates that the La Mula–Cupido aquifer may be in hydraulic communication with the hydrostratigraphic units above due to profound fractures and faults. Separated from the La Mula–Cupido aquifer by the La Peña aquitard and overlain by the Telephone Canyon Formation lies the Glen Rose aquifer. Glen Rose wells drilled in the Burro and Peyotes anticlines encountered fresh (TDS < 1,000 mg/l) groundwater. Five regionally important springs (Zaragoza, Morelos, Nava, Allende, and Villa Union) located outside the Glen Rose subcrop area are interpreted as manifestations of Glen Rose aquifer discharge (Leal, 1992).

### **Fredericksburg and Lower Washita groups**

The Fredericksburg and lower Washita rocks are the primary water-producing strata in the study area. They consist of rocks of the Devils River Formation and of rocks of the Maverick basin (the Salmon Peak and McKnight formations).

The Devils River Formation is “one of the most porous and permeable” formations in the study area and displays extensive karst development (Clark and Small, 1997). The Devils River Formation is a prolific fresh-water aquifer in central Val Verde County and parts of Kinney and Uvalde counties.

Rocks of the Maverick Basin (the Salmon Peak and McKnight formations) underlie most of Kinney, southern Val Verde, and southeast Uvalde counties. The upper Salmon Peak Formation is permeable and porous and yields fresh to saline groundwater to wells. The lower Salmon Peak Formation has low permeability and porosity, but can produce groundwater from fractured intervals (Barker and others, 1994). The McKnight Formation generally displays low permeability and porosity and is classified as a confining unit (Clark and Small, 1997). Brecciated sections in the lower McKnight Formation can produce moderate amounts of groundwater high in sulfate and chloride. The West Nueces Formation yields groundwater to wells primarily from its “moderately permeable” upper part, whereas the lower members are “almost impermeable” (Barker and others, 1994). In Northern Coahuila, the West Nueces, McKnight, and Salmon Peak formations crop out extensively throughout the Serranía del Burro where they are the main water-bearing units. Batzner (1976) investigated the chemical character of shallow groundwater and springs in the Peyotes area and concluded that the Fredericksburg strata in the El Burro area and Lomerio Peyotes are hydraulically connected.

Outside the Maverick Basin and to the north of the Devils River Trend lie the Fort Terrett (of the Fredericksburg Group) and Fort Lancaster formations, the latter comprising the Lower Washita Group. The Fort Lancaster Formation can become water-saturated in north-central Val Verde County. The Fort Terrett Formation’s “burrowed zone” and the

brecciated “Kirschberg evaporite zone” are highly permeable and the most important water-bearing units in the Edwards Plateau (Barker and others, 1994).

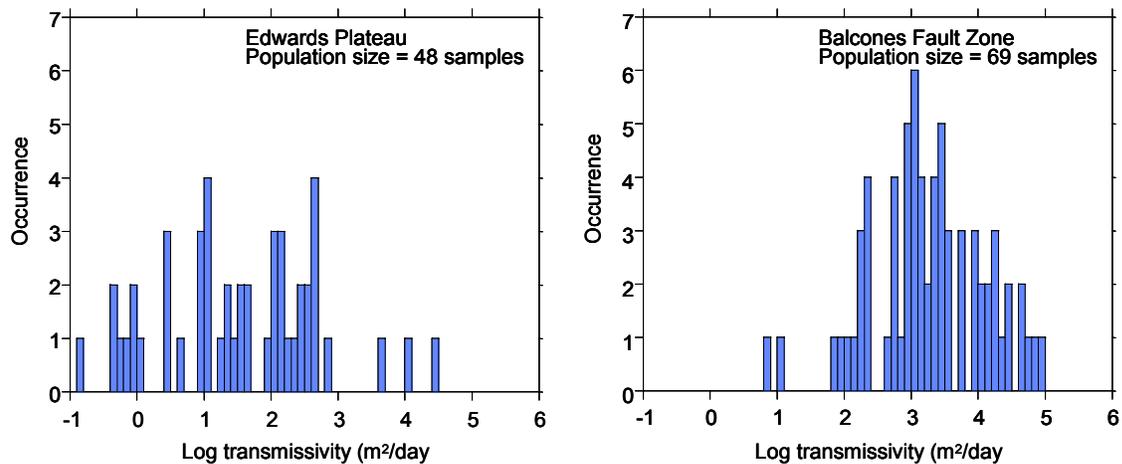


Figure 4-5: Histograms of transmissivity for the Edwards–Trinity aquifer in Texas (data from Texas Water Development Board’s groundwater database).

## Aquifer properties

Few aquifer test data are available for the Texas side of the study area, while no such information could be located for Mexico. However, specific capacity data for 119 wells mostly in Uvalde and Val Verde counties were available in the TWDB groundwater database. Aquifer transmissivity estimates were computed using an automated algorithm developed by Mace (2001). In the absence of aquifer test data, well yields were used as proxy for transmissivity and hydraulic conductivity on the Mexican side of the study area.

Histograms show transmissivity (Figure 4-5) and hydraulic conductivity (Figure 4-6) for two subareas: the Edwards Plateau and the Balcones Fault Zone. The Edwards Plateau subarea encompasses parts of Val Verde, Edwards, Kinney and Uvalde counties commonly associated with the Edwards–Trinity (Plateau) aquifer. The Balcones Fault Zone includes portions of Kinney and Uvalde counties east of the Brackettville groundwater divide. Transmissivity and hydraulic conductivity each span several orders of magnitude, which is typical for carbonate rocks in karstic terranes.

In the Edwards Plateau, transmissivity ranges from 0.15 to 25,100 m<sup>2</sup>/day, and hydraulic conductivity ranges from 0.0009 to 221 m/day, with median values of 38 m<sup>2</sup>/day and 0.7 m/day, respectively. The distributions of these parameters are uneven and suggest heterogeneity induced by multiple sample populations. Parameter distribution may illustrate distinct but overlapping populations controlled by both matrix and fracture permeability but could also be due to insufficient number of samples. In the Balcones Fault Zone, transmissivity ranges from 7 to 97,300 m<sup>2</sup>/day, and hydraulic conductivity

ranges from 0.2 to 2,400 m/day, with median values of 1,935 m<sup>2</sup>/day and 36 m/day, respectively. Parameter distributions (Figures 11-5, 11-6) are closer to lognormal.

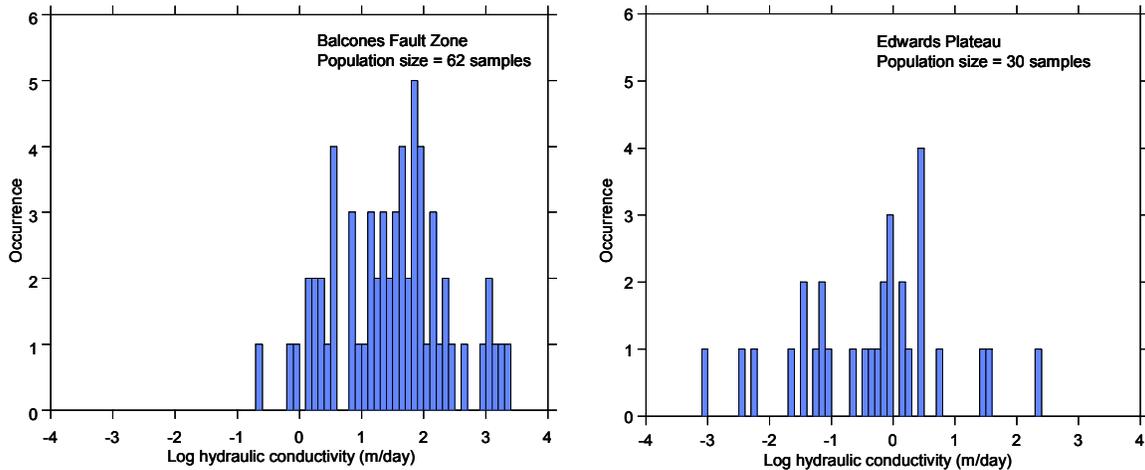


Figure 4-6: Histograms of hydraulic conductivity for the Edwards–Trinity aquifer in Texas (data from Texas Water Development Board’s groundwater database).

The more even histogram grouping could be indicative of a single predominant control over aquifer permeability, possibly the effect of fractures. Most of the wells in the study area have transmissivities of up to 20,000 m<sup>2</sup>/day. Transmissivity values of up to 90,000 m<sup>2</sup>/day were calculated in parts of Uvalde County. These values are in agreement with the transmissivity estimates used by Kuniansky and Holligan (1994) in their numerical groundwater flow model for the Edwards–Trinity aquifer system. In Val Verde, Edwards, and northern Kinney counties, Kuniansky and Holligan (1994) estimated transmissivities ranging from 465 to 10,000 m<sup>2</sup>/day in the Edwards Plateau and from 9,300 to 45,000 m<sup>2</sup>/day around Del Rio and in east of the Brackettville divide.

Kuniansky and Holligan (1994) estimated transmissivities ranging from 46,500 m<sup>2</sup>/day to 460,000 m<sup>2</sup>/day in southeast Uvalde County. Well yields in the Coahuila part of the Edwards–Trinity aquifer vary greatly. Most of the area wells with available yield data produce water from the Cretaceous bedrock. Well yields of 0.5 to 16 l/s are reported in the Serranía del Burro and on mountain flanks where the aquifer is predominantly unconfined (INEGI, 1979). Well yields increase in the confined area of the aquifer where 20 to 400 l/s are reported south of Ciudad Acuña and near Amistad Reservoir (INEGI, 1979).

## Potentiometric surface and water levels

Water-level data from 136 wells in Texas and Coahuila were collected between January 1980 and December 1981. Figure 4-7 shows the potentiometric surface of the Edwards–Trinity aquifer built using those data.

The 1980-81 potentiometric surface slopes towards the Rio Grande with hydraulic gradients of 0.016 in the uplands of Serranía del Burro and 0.006 along the Edwards very

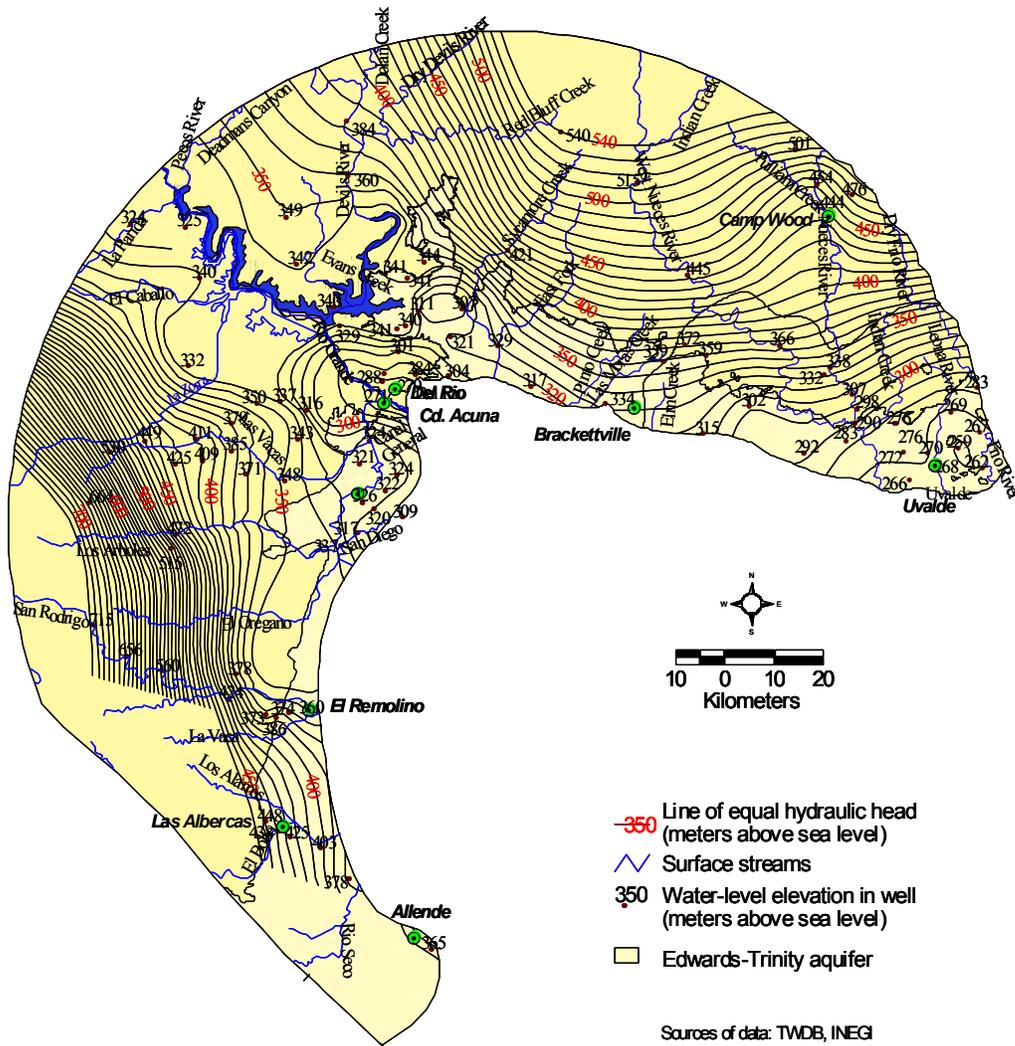


Figure 4-7: Potentiometric surface map for the Edwards–Trinity aquifer (data for 1980-1981).

flat ( $\sim 0.0001$ ) immediately south of Amistad Reservoir and in Val Verde County west of Devils River. The hydraulic gradient becomes steeper (0.003) in the Del Rio–Ciudad Acuña area. Hydraulic heads in excess of 715 m in the Burro area and 540 m in the Edwards Plateau define areas of groundwater recharge. The hydraulic gradient is very flat ( $\sim 0.0001$ ) immediately south of Amistad Reservoir and in Val Verde County west of Devils River and becomes steeper (0.003) in the Del Rio–Ciudad Acuña area. Hydraulic heads in excess of 715 m in the Burro area and 540 m in the Edwards Plateau define areas of groundwater recharge.

The flat hydraulic gradient near Amistad Reservoir and northeast of Uvalde suggests that the aquifer there is very transmissive and large amounts of groundwater may flow through it. Groundwater moves generally from the highlands in Coahuila and Texas towards Amistad Reservoir or Rio Grande where hydraulic heads range from 270 m to 340 m above sea level. Surface drainage variations as well as groundwater pumping can modify the regional potentiometric pattern. Gaining stream conditions in rivers such as Devils, Sycamore, and Nueces in Texas and Arroyo Las Vacas, Río San Diego, Río San Rodrigo, and Río Escondido in Coahuila cause the contour lines in Figure 4-7 to flex upstream along the river channel. A mild pumping cone of depression has reversed the hydraulic gradient northeast of Uvalde.

In 1980, the depth to groundwater in study area wells varied between 1.9 m and 112 m with an average of 25.8 m. Depths to water of less than 15 m were measured in wells in the low-lying areas around Del Rio and Ciudad Acuña along river courses and creeks in the Lomerio Peyotes area and north and west of Uvalde.

Deeper water levels of up to 112 m were generally encountered in the Edwards Plateau of Texas and Serranía del Burro in Coahuila. Because well depth and completion information are unavailable for Mexico, it can not be verified at this time whether the shallow water levels measured in Lomerio Peyotes are representative of Edwards–Trinity aquifer conditions or not. In this area where the aquifer is confined, the Fredericksburg strata is overlain by rocks of the Eagle Ford Group (Gulf Series), which is known to yield moderate quantities of water to wells in Kinney County, Texas. However, Batzner (1976) concluded, based on structural and geochemical evidence, that Edwards–Trinity groundwater from the Burro region moves through the subsurface towards Lomerio Peyotes where it upwells into the overlying strata.

Time series hydrographs of selected Texas wells (Figure 4-8) illustrate long-term temporal water-level fluctuations. Water-level fluctuations are caused by changes in aquifer storage, which is a function of recharge and discharge. Several wells located immediately adjacent to Amistad Reservoir exhibited pronounced increases in water levels soon after the lake was emplaced in 1968. Net water-level changes of up to 80 m have been measured in some Val Verde County wells, and it took approximately seven years for the groundwater levels to stabilize (Figure 4-8). The effects of this increase in aquifer storage extended to the southeast all the way to Del Rio and as far as 40 km north of the reservoir (Armstrong, 1995). Since the completion of the reservoir, baseflow from streams and creeks in both Texas and Chihuahua have increased by more than 77 percent for treaty streams and 228 percent for non-treaty streams, and a large number of springs that formerly flowed into the reservoir area were inundated (IBWC, 1990).

Hydrographs for selected wells in the Edwards Plateau between Del Rio and Uvalde are characteristic of areas with little or no groundwater development as denoted by rather stable water levels over time with only minor seasonal variations. Fluctuations in aquifer storage in this region are explained by the interplay of cyclical precipitation patterns and well withdrawals (Barker and others, 1994). In contrast, water levels in several Uvalde County wells have fluctuated as much as 40 m from the mid 1950s through the mid-

1960s and 20 m since the mid-1980s while being on a slightly ascending trend (Figure 4-8).

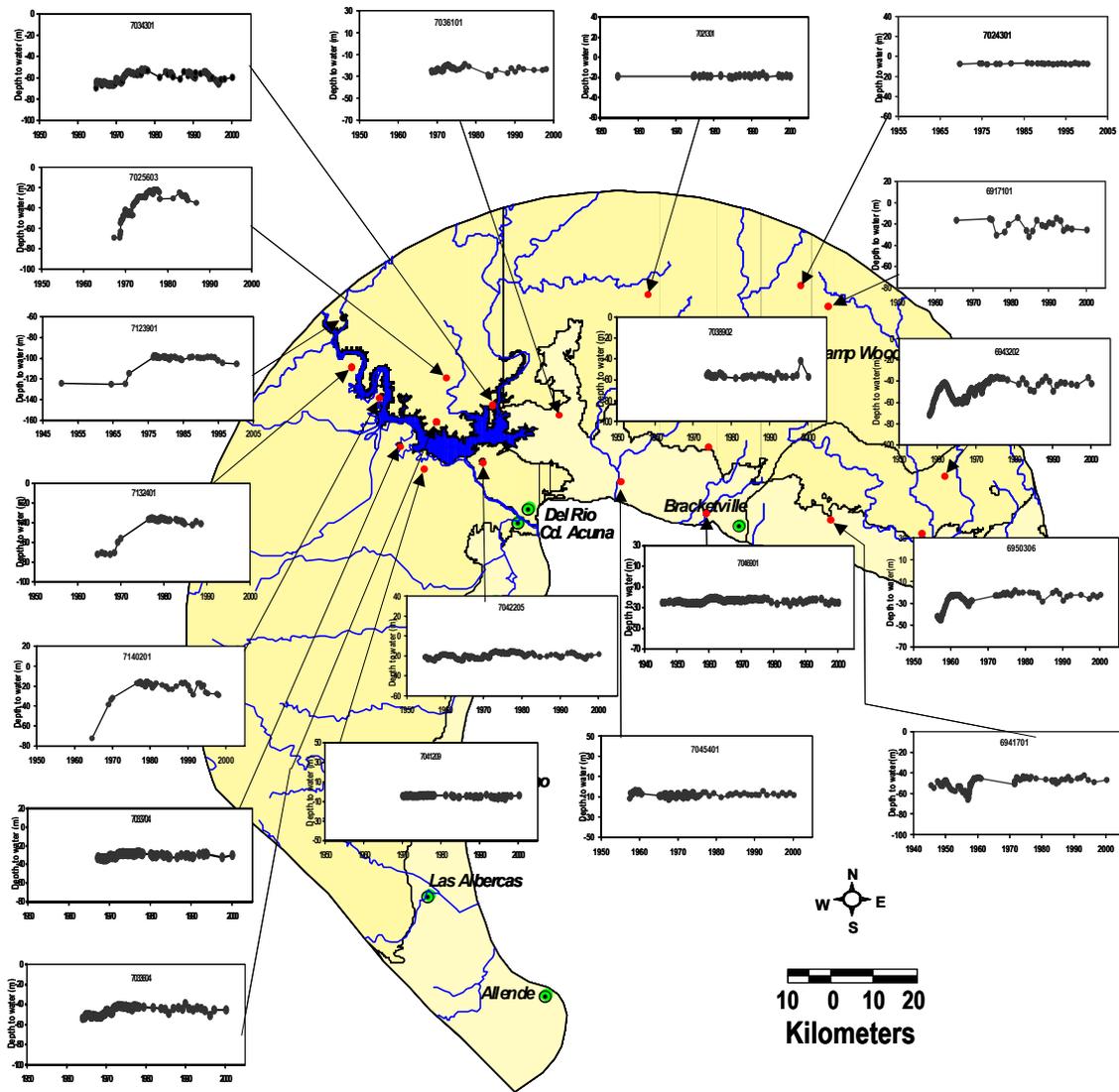


Figure 4-8: Well hydrographs for the Edwards–Trinity aquifer (data from Texas Water Development Board’s groundwater database).

## Recoverable groundwater resources

Several studies have been conducted in Texas to estimate the amount of recoverable fresh (TDS < 1,000 mg/l) water in the Edwards–Trinity aquifer in the study area. Calculations require an estimate of the volume of water-saturated rock and an estimate of the

storativity of the aquifer, which can vary from  $10^{-7}$  for confined aquifers to 0.4 for unconfined aquifers (Domenico and Schwartz, 1990). Recoverable resources are computed by multiplying the storativity by the volume of the aquifer holding fresh groundwater.

The volumes of groundwater available in the year 2000 from the Edwards–Trinity aquifer for the Texas side of the study area were determined using ArcView® GIS map algebra techniques. First, the volume of the saturated portion of the aquifer (rock and water) was computed by multiplying the surface area of the study region by the saturated thickness of the aquifer.

The saturated thickness was calculated by subtracting the elevation of the aquifer bottom (Barker and Ardis, 1992) from the water-level elevations in wells as measured during year 2000. To account for the less productive Trinity strata, a storativity of 0.015 and a 25 percent recoverable yield were applied to the total saturated volume to arrive at a total of 11,231 hm<sup>3</sup> estimated recoverable groundwater reserves. Recoverable groundwater values are approximate due to uncertainty in estimates of aquifer-saturated thickness and spatial variability of specific yield. Due to the paucity of geologic and aquifer properties data in Mexico, no attempt has been made to estimate recoverable groundwater resources within Coahuila.

## **Recharge areas**

Mechanisms of recharge to the Edwards–Trinity aquifer system in the Edwards Plateau are different from those active in the Balcones Fault Zone. In the Edwards Plateau, recharge is mostly by direct infiltration of precipitation and streamflow on the outcrops of Trinity, Fredericksburg, and lower Washita strata. A small amount of recharge may occur along faults and fractures and by cross-formational flow through semi-confining beds.

Solution-widened fractures and sinkholes facilitate the recharge to the Edwards Plateau section of the aquifer in Texas. These solution features are particularly abundant on the steeper slopes and in the beds of streams on the southern edge of the Edwards Plateau but tend to be less common elsewhere. The Edwards–Trinity aquifer in Val Verde, Edwards, and Kinney counties has a recharge area of approximately 16,800 km<sup>2</sup> in size. It extends from Lozier Canyon in Terrell County north to Sheffield in Pecos County, east–northeast from Sheffield to Eldorado in Schleicher County, southeast from Eldorado to Bracketville in Kinney County, and west to Del Rio (Reeves and Small, 1973).

In the Balcones Fault Zone, the aquifer is recharged by the perennial streams crossing highly permeable rocks of the Devils River Formation; by direct infiltration of precipitation on the aquifer outcrop; and by cross-formational flow from the adjacent Trinity aquifer (Barker and others, 1994).

Various researchers have estimated the amount of recharge to the Edwards–Trinity aquifer in the study area based on streamflow measurements and base-flow separation techniques and expressed it as fraction of annual rainfall reaching the aquifer. The long-

term recharge rates for Real, Kinney, and Edwards counties are 50.8 mm/year (Long, 1958), 35.6 mm (Bennett and Sayre, 1962), and 33.02 mm/year (Long, 1963), respectively. Reeves and Small (1973) calculated the yearly recharge rate in Val Verde County to be approximately 38.1 mm. In the development of their groundwater flow model, Kuniansky and Holligan (1994) estimated recharge rates for the year 1974 ranging from 6.32 mm in Val Verde and western Kinney and Edwards counties to over 100 mm in portions of Uvalde County. Mace and Anaya (2003) revisited Bennett and Sayre's (1962) estimates of average annual recharge in Kinney County. Errors in values used for streamflow and recharge area have been identified that resulted in Bennett and Sayre's (1962) overestimation of Kinney county recharge for the period 1939 to 1950. The correct average annual recharge, according to Mace and Anaya (2003), should be 57.5 hm<sup>3</sup> from 1939 to 1950 and 86.1 hm<sup>3</sup> for the full period of record (1939-1950 and 1956-2001).

During January 2002, the author collected six groundwater samples from wells and springs in Val Verde, Edwards, and Kinney counties and had them analyzed for stable and radiogenic isotopes. Deuterium ( $\delta^2\text{H}$ ) and Oxygen-18 ( $\delta^{18}\text{O}$ ) are stable isotopes used to investigate the provenance of groundwater, and tritium ( $^3\text{H}$ ) and Carbon-14 ( $^{14}\text{C}$ ) are radioisotopes used to determine the age of the water. The results are shown in Table 4-1.

A graph of  $\delta^2\text{H}$  and  $\delta^{18}\text{O}$  (Figure 4-9) shows the samples plotting on or slightly below the Global Meteoric Water Line (GMWL) (Craig, 1961). The proximity of the data points to GMWL indicates that the groundwater originated as precipitation and also that  $\delta^2\text{H}$  and  $\delta^{18}\text{O}$  values have not been altered significantly by water-rock interaction (Banner and Hanson, 1990). The data describe a trend line with a slope of almost 5, which is typical of evaporative isotope enrichment (Clark and Fritz, 1997, p. 86). This suggests that the Edwards–Trinity aquifer is dominated by recharge from summer rains—characterized by larger isotope fractionation effects—as opposed to winter rains which, in arid climates, tend to plot closer to the global line (Clark, 1987). Water can be lost by evaporation from surface waters during runoff prior to infiltration, during infiltration through the unsaturated zone, or from the water table if it is shallow enough. The trend line slope being close to five suggests that the former may be the predominant evaporation mechanism (Clark and Fritz, 1997).

Table 4-1: Isotope composition in Edwards–Trinity groundwater samples from Val Verde, Edwards, and Kinney counties.

State Well Number	$\delta^2\text{H}$ (‰) SMOW	$\delta^{18}\text{O}$ (‰) SMOW	Apparent $^{14}\text{C}$ Age <sup>1</sup>	pmC <sup>2</sup>	$\delta^{13}\text{C}$ (‰)	Tritium (TU) <sup>3</sup>
55-44-801	-33.5	-5.10	2870±40	0.6990	-10.6	1.14
70-41-301	-33.5	-5.30	2400±40	0.7410	-11.8	1.85
71-15-401	-37.5	-5.95	8130±40	0.3630	-9.6	0.79
70-45-505	-32.5	-4.90	4030±40	0.6050	-10.3	2.01
55-63-702	-36.0	-5.30	5960±40	0.4760	-8.4	0.98
70-29-101	-33.5	-5.10	2650±50	0.7190	-11.1	2.64

<sup>1</sup>Reported as radiocarbon years before present (“present” = 1950 A.D.).

<sup>2</sup>Percent modern carbon.

<sup>3</sup>Tritium Units

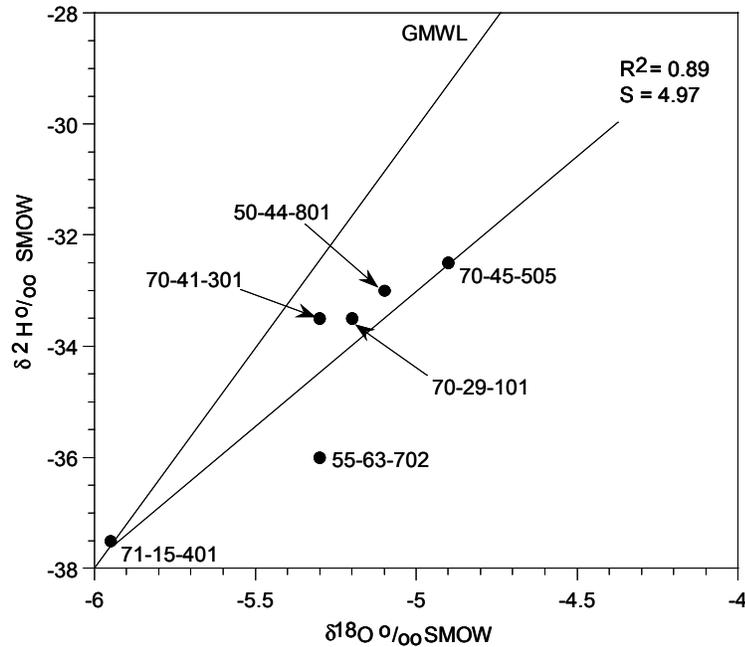


Figure 4-9: Plot of  $\delta^2\text{H}$  versus  $\delta^{18}\text{O}$  values for Edwards–Trinity aquifer. Data plot along an evaporation line, indicating evaporative enrichment of water prior to recharge. Source of data: Texas Water Development Board’s groundwater database.

Tritium concentrations greater than 0.8 TU, coupled with radiocarbon activities ranging from 36 to 74 pmC, indicate that the samples represent a mixture between submodern (recharged prior to 1952) and recently recharged groundwater. Tritium and radiocarbon in groundwater vary in a non-uniform fashion along flow paths in the aquifer. The existence of preferential flow conduits permitting fast, focused recharge to the water table with limited mixing taking place could explain this behavior.

Recharge to the Coahuila part of the Edwards–Trinity aquifer occurs both inside and outside the study area by infiltration of rainwater on the outcrops of Trinity, Fredericksburg, and lower Washita strata and by seepage along various streambeds. The recharge zone of the Trinity portion of the aquifer corresponds with the extensive Glen Rose outcrops throughout Serranía del Burro arroyos and canyons incised in the mountain.

The Fredericksburg and lower Washita groups of the Maverick Basin are recharged through the southern flank of Serranía del Burro (Leal, 1992). Recharge to the Devils River Formation in Coahuila takes place along San Juan Valley to the west of Nueva Rosita, Coahuila (Leal, 1992).

## Discharge Areas

Groundwater discharges from the Edwards–Trinity aquifer as springs and seeps, as baseflow to gaining streams, and through well withdrawals. Locally, where the water table is shallow, some discharge may take place by evapotranspiration.

Most of the discharge from the Edwards–Trinity aquifer in the study area is by springflow. Among the largest springs on the Texas side are San Felipe, Goodenough, and Las Moras Springs. San Felipe Springs, the fourth largest in Texas (Brune, 1981), issues from ten orifices along San Felipe Creek northeast of Del Rio in Val Verde County. The City of Del Rio relies in part on the springs for their water supply. From 1961 through 1967, San Felipe Springs discharged an average of 2.26 m<sup>3</sup>/s (IBWC, 2001). The filling of Lake Amistad with water has resulted in increased springflows of 3.38 m<sup>3</sup>/s on average since 1968.

Goodenough Springs, also called Hinojosa Springs, are now submerged by Amistad Reservoir. Before 1968, when they were inundated by the lake, they were the third largest group of springs in Texas with an average flow of 3.9 m<sup>3</sup>/s (Brune, 1981). Now 46 m under the top of the lake, their flow is reduced due to the hydraulic pressure induced by the column of water above the springs' orifice. Underwater investigations by cave divers have revealed that the springs still discharge a significant amount of water (M. Gary, 1999, personal communication). Las Moras Springs rise on the grounds of Fort Clark in Bracketville, Texas, and, with an average flow of 0.622 m<sup>3</sup>/s, was the ninth-largest spring in the state (Brune, 1981). Until 1964, when they temporarily ceased flowing, Las Moras Springs had been the sole public water source for the City of Bracketville, which has since switched to water wells. Presently, the springs are feeding a large pool used by a vacation resort.

In Coahuila there are no less than 13 major springs grouped in a relatively small area (700 km<sup>2</sup>) encompassing the cities of Zaragoza, Morelos, Nava, Allende, and Villa Union (Figure 4-1). Most of the springs issue from Tertiary and Quaternary conglomerates and upper Cretaceous limestone at the northern edge of Peyotes anticline. Nevertheless, Elizondo (1977) and Leal (1992) have determined that these springs are fed by Glen Rose Limestone and Salmon Peak Formation groundwater recharged in the Serranía del Burro to the northwest. Table 4-2 lists several springs and their flow as measured by SARH technicians at various times from 1971 through 1976. Smaller springs have been identified throughout Serranía del Burro on the several ranches outside the study area (Leal, 1992).

Pumping from the Edwards–Trinity aquifer in Texas is for municipal, industrial, irrigation, and livestock water-supply purposes. From 1980 through 1997, an average of 155.92 hm<sup>3</sup> of Edwards–Trinity groundwater was used every year to meet the needs within Val Verde, Edwards, Kinney, and Uvalde counties. More water was used for irrigation than for any other purpose in the study area. From 1980 to 1997, irrigation pumpage was on average 137.74 hm<sup>3</sup> or 88.3 percent of the total amount of Edwards–Trinity groundwater used every year. Irrigation pumping in Uvalde County has been on average 82 percent of the total groundwater extracted area-wide for all uses. Yearly

Table 4-2: Flow from selected springs in Coahuila (data from Elizondo, 1977).

Spring Name	Springflow (m <sup>3</sup> /s)					
	Sept. 1971	Apr. 1974	Oct. 1974	Jan. 1976	Feb. 1976	Apr. 1976
Allende	1.386	1.200	1.205	1.499	1.542	1.462
Chamacueros	0.060	0.060				
Las Corrientes	1.566	1.566	0.846			
Villagigedo		0.200	0.093			
Guadalupe	0.150	0.150	0.211		0.407	0.433
La Zanja	1.696	1.775				1.698
Patinos	0.336	0.200				
Morelos		1.500		1.707	1.552	1.288
El Socavon	1.200	1.200	0.900			
El Remolino	0.520	0.830	0.583			
Nava		1.100	1.41			
Las Albercas		0.300				

municipal pumping accounted for 14.76 hm<sup>3</sup> or 9.5 percent of the groundwater use. Average annual livestock and industrial (manufacturing, power, and mining) uses were 2.39 hm<sup>3</sup> (1.5 percent) and 1.03 hm<sup>3</sup> (0.7 percent) respectively.

## Water quality

General groundwater quality in the Edwards–Trinity aquifer is shown on the Stiff map (Figure 4-10). The hydrochemical data displayed were collected in 1980-1981 in Coahuila and between 1981 and 2000 in Texas. Groundwater in both Coahuila and Texas was predominantly fresh (TDS < 1,000 mg/l). Several wells drilled near the downdip limit of the aquifer (the "bad-water zone") in both Texas and Coahuila had higher TDS concentrations of up to 2,970 mg/l. Low-TDS groundwater, indicated by the narrow Stiff diagrams in Figure 4-10, is associated with active recharge areas in the Edwards Plateau and in Serranía del Burro and Lomerio Peyotes. TDS concentrations increase downgradient where sites located near Nava, Allende, Villa Union, and San Carlos, Coahuila, and north of Camp Wood, Texas, showed TDS concentrations in the 1,000 to 3,000 mg/l range.

The presence of 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. Samples from 212 wells within the study area were analyzed for major and minor ions. Of these, 16 samples showed sulfate concentrations of 300 mg/l or higher and five samples had nitrate (as NO<sub>3</sub><sup>-</sup>) concentrations greater than 44.3 mg/l.

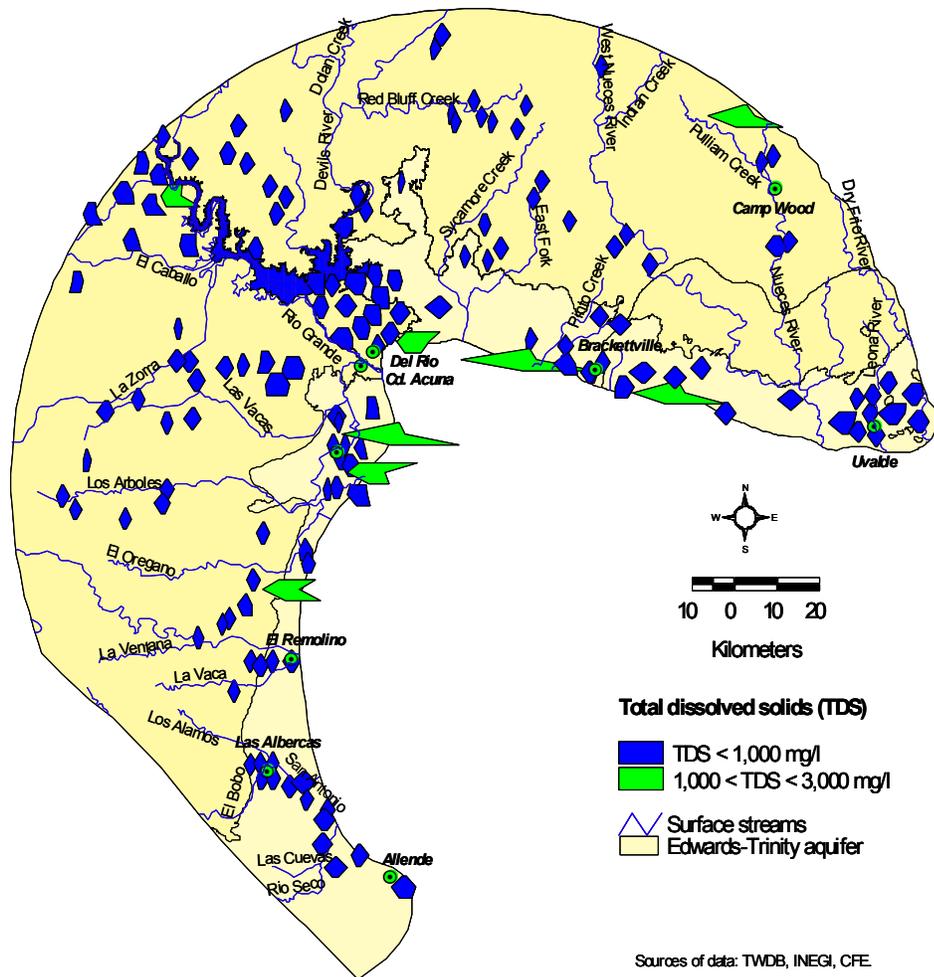


Figure 4-10: Stiff diagrams illustrating hydrochemical facies for the Edwards–Trinity aquifer.

Four general water types could be identified based on their hydrochemical signatures:

- 1) A Ca-HCO<sub>3</sub> type which is predominant (76 percent of all samples) throughout the Edwards–Trinity aquifer in both Coahuila and Texas. Fresh (less than 1,000 mg/l TDS) Ca-HCO<sub>3</sub> groundwater occurs not only in the highlands of Serranía del Burro and Edwards Plateau but also in wells along the mountain fronts.
- 2) A Ca-SO<sub>4</sub> type encountered primarily in fresh and slightly saline wells dotting the downdip limit of the aquifer in both Texas and Coahuila and in few isolated wells around Brackettville and Camp Wood, Texas.
- 3) A Ca–mixed anion type where no single anion species exceeds 50 percent of the total anion equivalent weight, and calcium is the dominant cation. Within this

water type, a Ca-HCO<sub>3</sub>-SO<sub>4</sub> sub-facies has been identified in wells west of San Carlos in Coahuila and just north of Del Rio in Texas. Several samples near Uvalde and one just east of Del Rio show a Ca-HCO<sub>3</sub>-Cl signature.

- 4) A mixed cation-mixed anion type where the ion with the greatest concentration is less than 50 percent of the total ionic equivalent weight.

Fresh waters (less than 1,000 mg/l TDS) have been sampled in the Del Rio–Acuña area wells and at several locations along the Rio Grande upstream from Amistad reservoir. Figure 4-12 illustrates potential evolutionary paths for Edwards–Trinity aquifer groundwater. Fresh, type 1 waters gradually change their composition down gradient to the more saline types 3 and 4 through the addition of Cl and Na ions and the loss of Ca and HCO<sub>3</sub>. These changes in chemical composition suggest that halite dissolution, calcite precipitation, and possibly ion exchange reactions may take place. Groundwater may evolve along a flow path from type 1 to type 2 through the addition of Ca, Mg, and SO<sub>4</sub> and loss of HCO<sub>3</sub>, consistent with the dissolution of calcite, dolomite, and evaporite minerals.

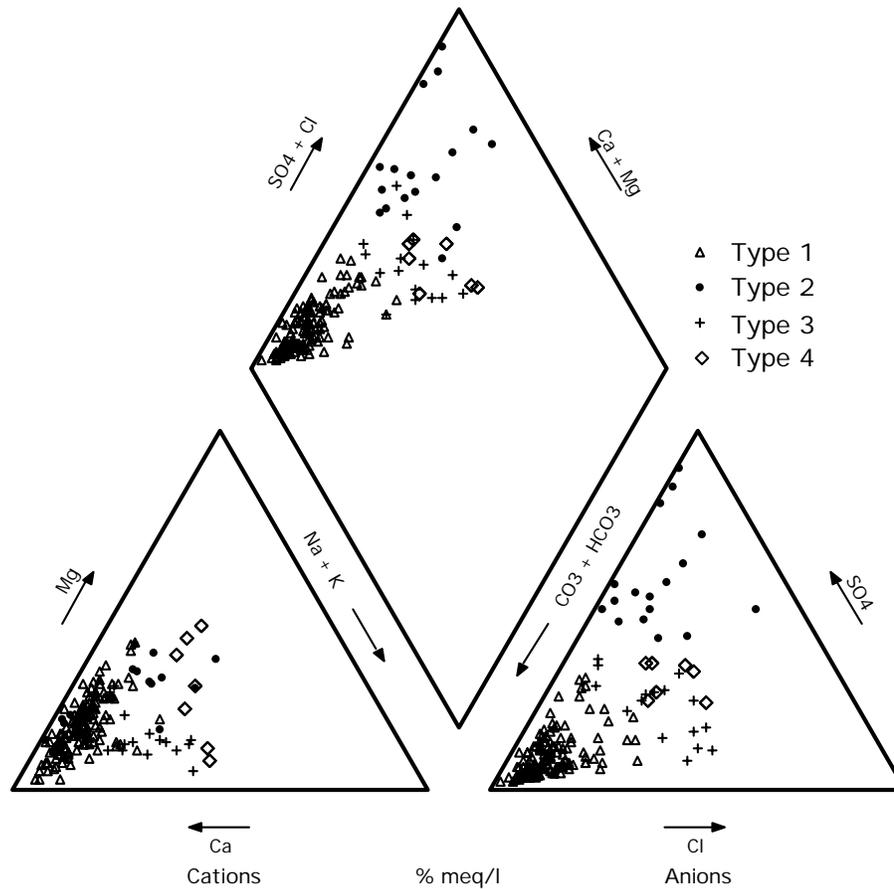


Figure 4-12: Piper diagrams showing major ion compositions for Edwards–Trinity aquifer (data from TWDB, INEGI, and CFE).

## Summary

The Edwards–Trinity aquifer underlies an area of 31,050 km<sup>2</sup>, of which 16,000 km<sup>2</sup> are located in Mexico. Cretaceous carbonates of the Trinity, Fredericksburg, and Washita groups host the Edwards–Trinity aquifer system, which, in the study area, is composed of two aquifers and the associated confining units. In the Edwards Plateau, transmissivity ranges from 0.15 to 25,100 m<sup>2</sup>/day and hydraulic conductivity ranges from 0.0009 to 221 m/day. In the Balcones Fault Zone, transmissivity ranges from 7 to 97,300 m<sup>2</sup>/day and hydraulic conductivity ranges from 0.2 to 2,400 m/day. Most of the wells in the study area have transmissivities of up to 20,000 m<sup>2</sup>/day. In Coahuila, well yields of 0.5 to 16 l/s are reported in the Serranía del Burro and on mountain flanks where the aquifer is predominantly unconfined. Well yields range from 20 to 400 l/s to in the confined area of the aquifer. Groundwater moves from the highlands in Coahuila and Texas towards Amistad Reservoir or Rio Grande with gradients of up to 0.003. Recharge to the Edwards–Trinity aquifer is mostly by direct infiltration of precipitation and streamflow in the aquifer outcrop. Groundwater discharges from the Edwards–Trinity aquifer as springs and seeps, as baseflow to gaining streams, and through well withdrawals. Groundwater in both Coahuila and Texas is predominantly fresh with total dissolved solids (TDS) concentrations below 1,000 mg/l. The presence of the sulfate and chloride ions suggests that the dissolution of evaporite minerals may have contributed to these samples' chemical composition.

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