Texas Aquifers Study

Groundwater Quantity, Quality, Flow, and Contributions to Surface Water

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December 31, 2016

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Executive Summary

Groundwater is a vital, yet hidden, natural resource that lies beneath Texas. More than 60 percent of water used in Texas comes from groundwater in 9 major and 21 minor aquifers. An aquifer is a geologic formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs. Major aquifers produce large amounts of fresh groundwater over large areas of the state, while minor aquifers produce smaller amounts of freshwater over large areas or larger amounts over smaller areas. There are also other aquifers in Texas that may represent significant local sources of groundwater. The major and minor aquifers, extending beneath 81 percent of the land area of Texas, include confined aquifers that are fully saturated, holding water under pressure, and unconfined aquifers that are partly saturated, where the water table surface is free to rise and decline.

This report presents information on the geology and hydrogeology of the confined and unconfined aquifers of Texas, including the quantity and quality of the groundwater that they contain, the volume of flows from the aquifers to the surface waters of the state, and the volume of flows between the aquifers. This report fulfills the requirements of House Bill 1232, which was passed by the 84th Texas Legislature and signed into law by Governor Greg Abbott on May 28, 2015. Key elements of the study are located in the report as shown below:

Study Requirement	Location in Report
Quantity and quality of groundwater in confined and unconfined aquifers	Chapter 2
Groundwater and surface water interactions	Chapter 3
Map identifying which aquifers are tributary and which are non-tributary	Figure 4-2
Map identifying the area and water quality of the confined and unconfined aquifers	Figure 1-1 Figure 1-2 Figure 2-3
Contribution of those aquifers to any surface flow of any water	Figure 3-1
Contribution of those aquifers to any other aquifer	Figure 5-2

Groundwater quantity

The total estimated quantity of fresh and brackish-to-saline groundwater in Texas aquifers is 16.8 billion acre-feet. Major aquifers contain an estimated 12.6 billion acre-feet of groundwater; minor aquifers contain an estimated 4.24 billion acre-feet of groundwater. Not all of this groundwater, however, is recoverable because of aquifer limits and the state of current technology. Between 25 and 75 percent of this volume may be recoverable, but this range does not account for possible economic, environmental, or legal consequences of such pumping.

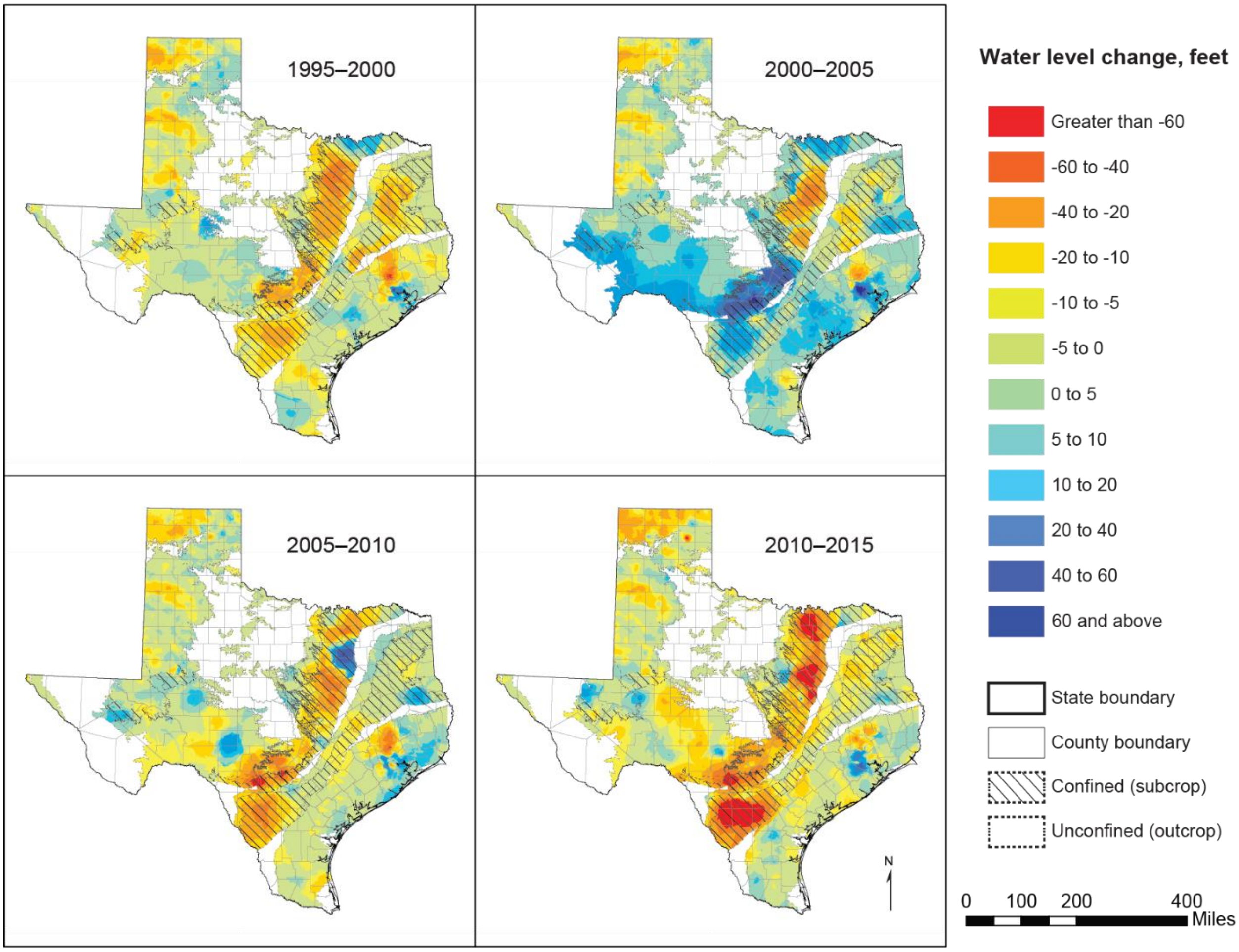
The Gulf Coast and Carrizo-Wilcox aquifers, in the coastal plains of Texas, cover about 30 percent of the state and account for two-thirds of the groundwater in storage. Although more groundwater is pumped from the Ogallala Aquifer than all other aquifers combined, the total recoverable groundwater storage remaining in this aquifer amounts to between 95.3 to 286 million acre-feet, or between 2 and 5 percent of the recoverable groundwater in storage in Texas.

Groundwater levels

Since 1895, over 1 million groundwater levels have been measured and are now accessible in the Texas Water Development Board (TWDB) groundwater database. Each year, the Texas Water Development Board, groundwater conservation districts, and the U.S. Geological Survey measure water levels in about 8,600 wells.

Groundwater levels in all major and minor aquifers have declined from predevelopment levels in response to development of groundwater resources for agricultural, municipal, and industrial uses. The annual volume of groundwater pumped in Texas increased rapidly in the 1950s and peaked at over 12 million acre-feet per year in the 1970s but has been between approximately 8 and 10 million acre-feet per year for the past 20 years.

Water levels in some areas have declined more than 100 feet between 1995 and 2015, generally in portions of confined aquifer systems with heavy pumping. The median water levels have declined statewide less than 2 feet per year during this period. Some groundwater declines have been reversed locally, such as in the Houston area, as pumping patterns change or recharge exceeds discharge.



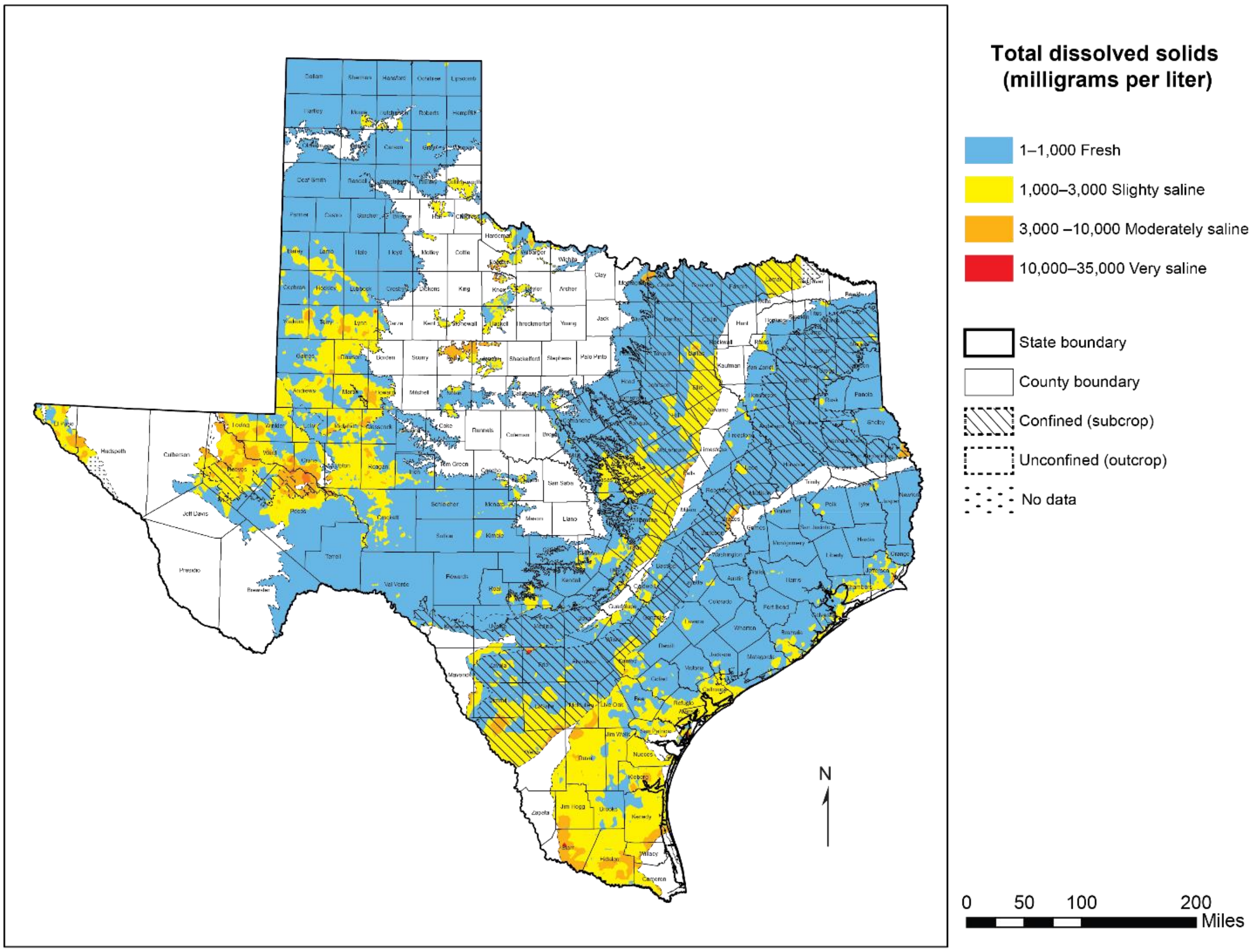
Water-level changes in the major aquifers of Texas (1995–2015).

Groundwater quality

Most groundwater in the major and minor aquifers is fresh, with total dissolved solids concentrations less than 1,000 milligrams per liter. In part this is because the official boundaries of many of the aquifers are determined based on water quality zonation; the water-bearing formation may continue beyond an aquifer boundary but contains more saline water.

Natural processes result in areas of higher total dissolved solids in some Texas aquifers, including the southern Ogallala, the Pecos Valley, the Seymour, and the southern Gulf Coast aquifers, and the down-dip confined areas of the Trinity and Carrizo-Wilcox aquifers. In some parts of the state, naturally-occurring levels of total dissolved solids, arsenic, and radionuclides, as well as high levels of nitrate from various sources, prevent the water from meeting drinking water standards.

The TWDB groundwater quality monitoring network has not detected significant changes in statewide groundwater quality over time.

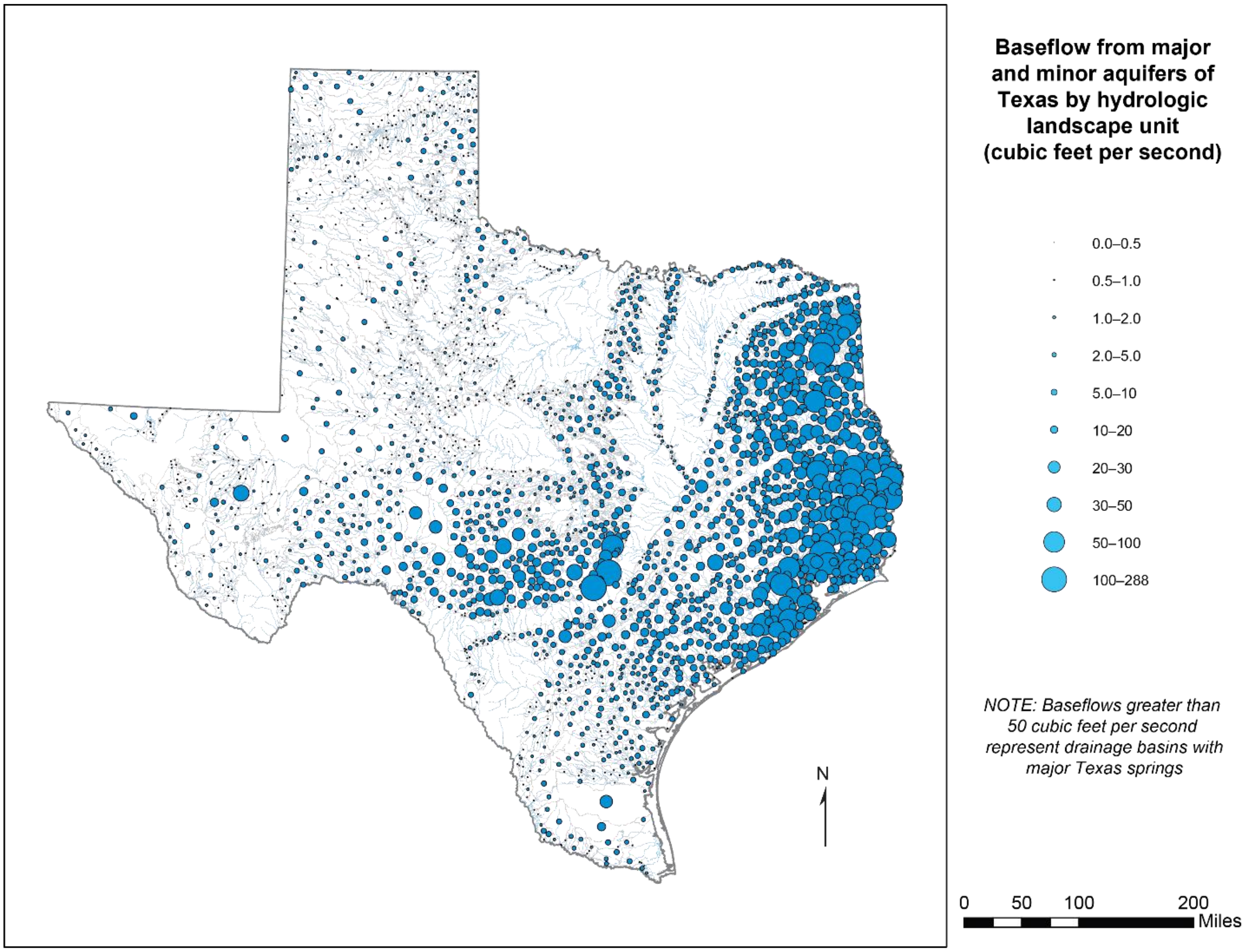


Concentration of total dissolved solids in major aquifers of Texas through 2015.

Groundwater and surface-water interactions

We estimated groundwater flow to surface water based on historical baseflow data from nearly 600 U.S. Geological Survey stream gaging stations in Texas. (Baseflow is the component of surface water flow that can be attributed to groundwater discharge to streams.) This estimate is derived from the use of “hydrologic landscape regions,” which provide a framework for regionalizing streamflow assuming that watersheds with similar slopes, soils, geology, and climate respond in the same way to precipitation and groundwater and surface-water interactions. This approach yielded an estimated average net groundwater flow to surface water of 9.3 million acre-feet per year, or about 30 percent of all surface-water flows. This average historical flow may not accurately represent current or future conditions and does not address the inherent variability of groundwater processes.

Groundwater contributions to surface water are greatest in East Texas and around major springs in the Hill Country and west Texas. The Gulf Coast Aquifer discharges the most groundwater to surface water, with an estimated flow of 3.8 million acre-feet per year. The Edwards (Balcones Fault Zone) Aquifer discharges the greatest volume of baseflow per square mile of aquifer area. Springs and seeps in West Texas also contribute locally significant baseflow to streams. About half of Texas aquifers contribute less than 50,000 acre-feet per year to surface-water flows.



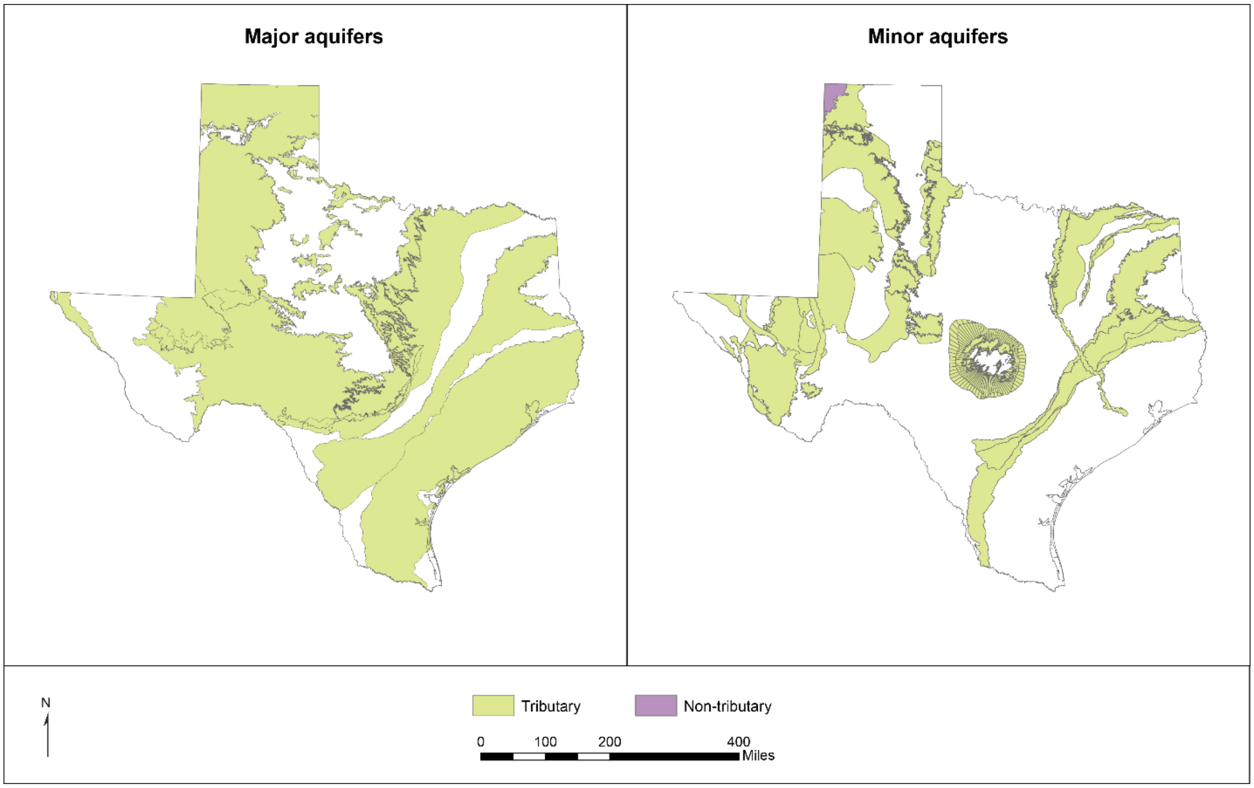
NOTE: Baseflows greater than 50 cubic feet per second represent drainage basins with major Texas springs

Baseflow from aquifers by hydrologic landscape unit (in cubic feet per second).

Tributary and non-tributary aquifers

The general definition that tributary groundwater is "groundwater that discharges into surface water" does not address how or where to distinguish between tributary and non-tributary aquifers. Our evaluation of streamflow data indicates that three major aquifers—the Edwards

(Balcones Fault Zone), Edwards-Trinity (Plateau), and Pecos Valley aquifers—contribute more than 50 percent of the baseflow of streams flowing across their outcrop zones on an average annual basis. This is supported by the number of current and historical springs that flow from these aquifers. Eighteen major and minor aquifers contribute between 20 and 50 percent of the flow to streams flowing over their outcrop zones. Eight minor aquifers contribute between 14 and 20 percent of the flow to streams flowing over their outcrop zones. These aquifers include the Blossom, Capitan Reef Complex, Dockum, Edwards-Trinity (High Plains), Igneous, Marathon, Nacatoch, and Woodbine aquifers. One minor aquifer, the Rita Blanca Aquifer, contributes zero percent to streamflow and is classified as non-tributary. Each of the state's aquifers has local areas that may differ from the regional, aggregate designation. For example, the confined areas of aquifers may exhibit characteristics that are non-tributary, whether or not they are tributary in their outcrop areas.

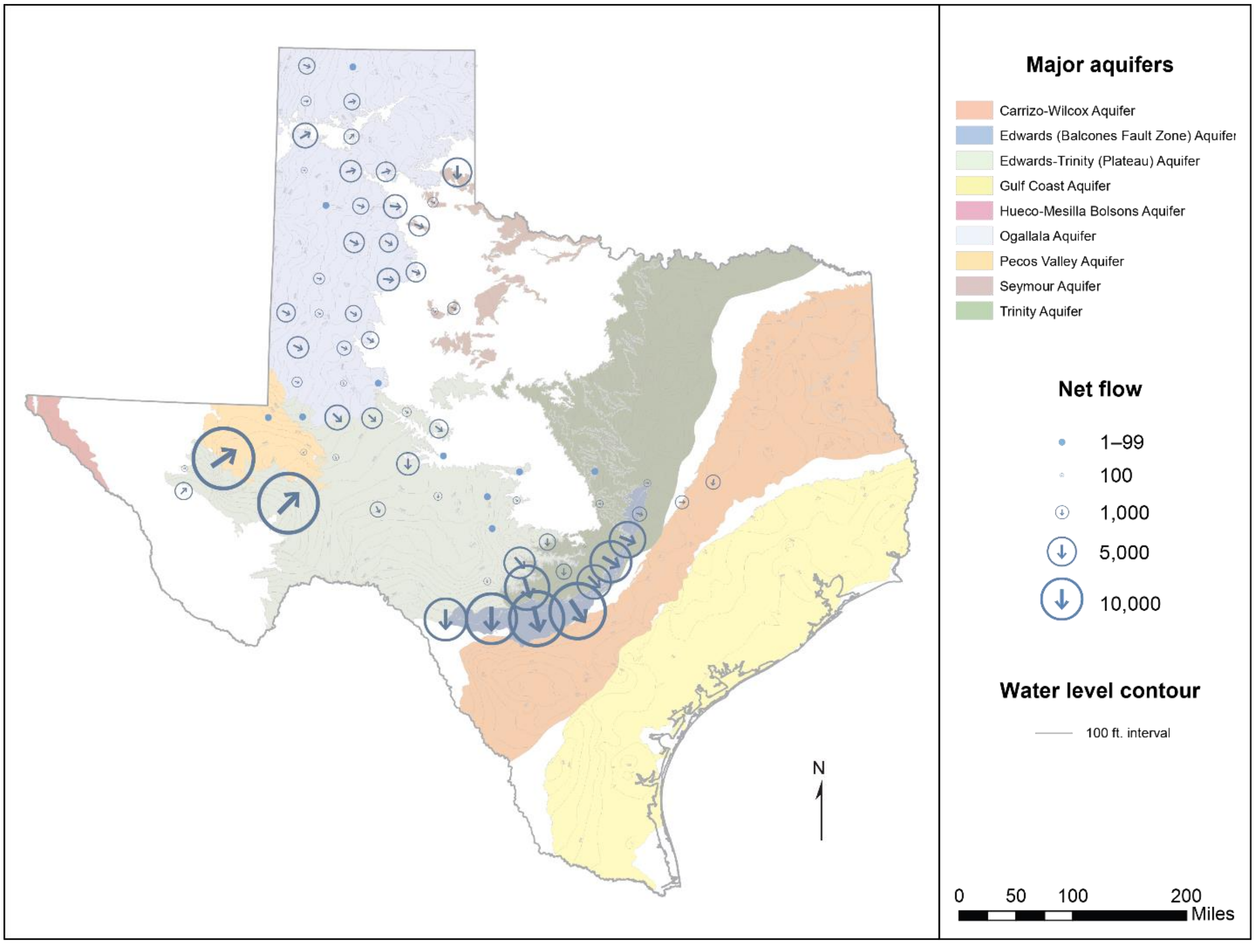


Map of the tributary and non-tributary aquifers of Texas.

Groundwater flows to other aquifers

Groundwater flow between aquifers has not been directly measured or monitored. Because of this lack of measurement, inter-aquifer groundwater flow has been estimated using groundwater availability models. These models, developed through the TWDB with stakeholder input, represent the best available compilation of hydrogeological data and processes with which to make such estimates. However, in most cases the models were not specifically designed or calibrated to estimate inter-aquifer flow. Aquifers bounded by low-permeability geological units have little or no interaction with neighboring aquifers. For these aquifers, the underlying confining layer is treated in the groundwater availability model as a no-flow boundary even though some flow could occur under certain pumping scenarios.

Groundwater modeling indicates that flows between aquifers occur primarily in the Hill Country and in the Pecos Valley. Smaller flows from the Ogallala into the Dockum occur in the High Plains. Groundwater flow between the major and minor aquifers in the eastern part of Texas is limited by the thick sequences of shale or clay that separate the aquifer systems and restrict vertical groundwater movement. Some aquifers in the central and western areas of the state are juxtaposed such that lateral groundwater flow probably occurs between them.



Relative magnitude of inter-aquifer flows where data or models are available.

Table of Contents

1 Introduction

Groundwater is a vital, yet hidden, natural resource that lies beneath Texas. More than 60 percent of water use in Texas is groundwater from 9 major and 21 minor aquifers. An aquifer is a geologic formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs. Major aquifers produce large amounts of fresh groundwater over large areas of the state, while minor aquifers produce smaller amounts of freshwater over large areas or larger amounts over smaller areas. There are also other aquifers in Texas that may represent significant local sources of groundwater. The major and minor aquifers, extending beneath 81 percent of the land area of Texas, include confined aquifers that are fully saturated, holding water under pressure, and unconfined aquifers that are partly saturated, where the water table surface is free to rise and decline. Although groundwater is largely unseen, it plays a major role in Texas' hydrological cycle. The Texas landscape collects rainfall and generates runoff above ground that can recharge groundwater systems, while below the surface, groundwater moves through the aquifers, reacts with the aquifer materials, and discharges to other aquifers or to surface water.

This report presents information on the geology and hydrogeology of the confined and unconfined aquifers of Texas, including the quantity and quality of the groundwater that they contain, the volume of flows between the aquifers, and the volume of flows from the aquifers to the surface waters of the state. This report fulfills the requirements of House Bill 1232, which was passed by the 84th Texas Legislature and signed into law by Governor Greg Abbot on May 28, 2015.

This study incorporates information from previous TWDB reports on the aquifers of Texas, including George and others (2011), Ashworth and Hopkins (1995), and Ashworth and Flores (1991). Significant study on groundwater-surface-water interaction is documented in Parsons (1999) and Scanlon and others (2005). Detailed water quality studies of major and minor aquifers have also been performed by various organizations under contract for the TWDB Groundwater Availability Modeling Program, funded by the Texas Legislature to improve the scientific basis for regional groundwater availability models. These reports, and the large body of research supporting the groundwater availability modeling program, have provided most of the information on the geology, structure, and hydrogeology of Texas aquifers presented in this report.

TWDB staff has performed a new analysis of water level and water quality data collected by the TWDB, the U.S. Geological Survey, and groundwater conservation districts. In addition, the

TWDB groundwater availability modeling group developed a new analytical process to quantify groundwater and surface-water interactions and modeled flows between aquifers.

Aquifer summaries, with additional information and details not included in the specific study requirements, are provided for context and background in Chapter 6.

1.1 Legislative background

House Bill 1232 requires the TWDB to conduct a study of the unconfined and confined aquifers of the state and directs the TWDB to determine the following:

1. the quantity and quality of groundwater in those aquifers,
2. whether those aquifers are tributary or non-tributary,
3. the contribution of those aquifers to any surface flow of any water in this state, and
4. the contribution of those aquifers to any other aquifer in this state.

The TWDB is required to produce a map that identifies the area and water quality of the confined and unconfined aquifers, a map that identifies which aquifers are tributary and which are non-tributary, and a report on the contribution of those aquifers to any other aquifer. In addition, House Bill 1232 requires that, before conducting the study, the TWDB "shall determine the minimum rate at which an aquifer must contribute to another aquifer in this state or to the surface flow of any water in this state in order to be included in the study."

On October 26, 2015, the TWDB held a public meeting to receive and discuss technical input regarding the minimum rate at which an aquifer must contribute to another aquifer or to the surface flow of any water in the state to be included in the study. More than 50 stakeholders contributed written input via email or through an online survey. The comments and suggestions covered a range of technical considerations, including both qualitative and quantitative metrics, to determine the flow requirements for the study.

Upon considering the statute, legislative intent, and input from stakeholders, the TWDB Board members met on January 19, 2016, to approve the following technical definitions:

1. The minimum flow rate between aquifers is defined as the lowest annual net vertical flow from an aquifer to another aquifer, as estimated by the applicable groundwater availability model. There are no available direct measurements or data related to the flow of groundwater between aquifers, so an indirect approach based on groundwater availability models is used. If no groundwater availability model exists or if the applicable groundwater availability model is insufficient, other appropriate methods may be used to estimate flow.

2. The minimum flow rate for groundwater discharge to surface water is defined as a contribution of at least 0.1 percent of the mean annual surface-water flow over any specified geographic area of any major or minor aquifer.

   Understanding aquifer contributions to surface water, and vice versa, is a major research topic in the field of groundwater hydrology. As a practical matter, springflow and streamflow measurements are few (when viewed over the entire state) and vary widely over time. Furthermore, aquifer contributions to surface water may be discrete (springs) or diffused along the length of a stream. To address this issue, we evaluated baseflow data—the component of surface-water flow that can be attributed to groundwater discharge to streams. The U.S. Geological Survey has conducted extensive, statewide studies involving hundreds of stream gages that have been used to prepare baseflow indices (Wolock, 2003). A baseflow index is the ratio of baseflow to streamflow expressed as a percentage of the streamflow. These baseflow indices are not aquifer-specific, so we compared these datasets of baseflow index values to the surface outcrops of Texas aquifers. Based on an initial review of the U.S. Geological Survey's baseflow index data for Texas, we determined that a minimum rate of 0.1 percent of the mean annual surface-water flow over any unit area of any specific aquifer maximizes the number of gage sites available for a statewide evaluation. Regardless of the baseflow index, we included all major or minor aquifers that have available springflow data in the study.

As a result of these definitions, this study evaluates flows between all major and minor aquifers in Texas and flows from groundwater to surface water for the entire area of the state.

1.2 Major and minor aquifers of Texas

Texas has numerous aquifers capable of producing groundwater for households, municipalities, industry, farms, and ranches. For the purpose of this study, the evaluation of unconfined and confined aquifers has been limited to the TWDB-designated major and minor aquifers of the state. The TWDB recognizes 9 major aquifers—aquifers that produce large amounts of water over large areas (Figure 1-1)—and 21 minor aquifers—aquifers that produce minor amounts of water over large areas or large amounts of water over small areas (Figure 1-2). These aquifers are critical sources of water for Texas, providing about 62 percent of the 13.7 million acre-feet of water used in the state in 2014, the latest year for which statistics are available. Groundwater represents about 85 percent of agricultural water, with irrigators withdrawing most of this water from the Ogallala Aquifer; 74 percent of all groundwater is used for irrigation, or 4.8 million acre-feet per year. About 36 percent of water used to meet municipal demands is from groundwater (TWDB, 2016).

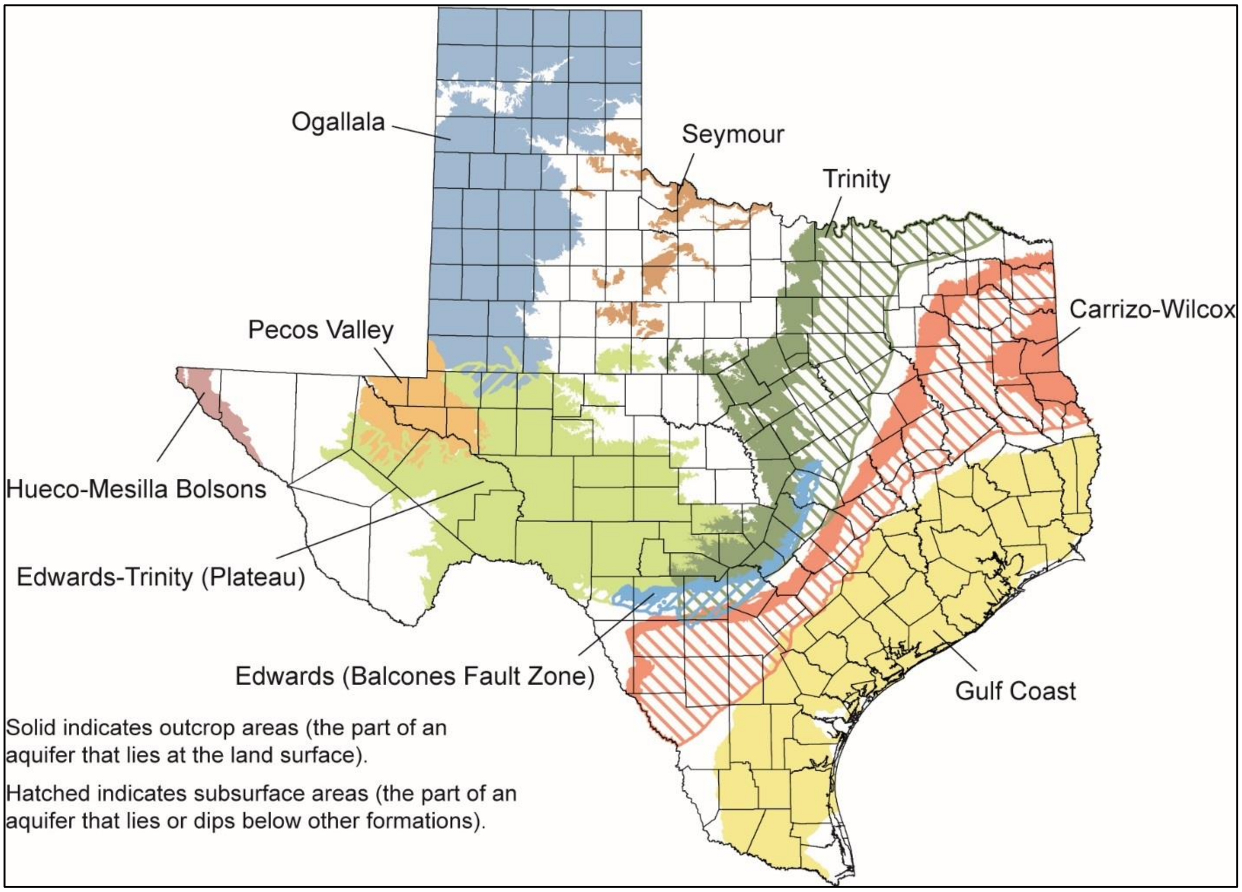


Figure 1-1. The major aquifers of Texas.

1.3 Confined and unconfined aquifers

Aquifers are geologic formations that contain sufficient saturated permeable material to yield significant quantities of water to wells and springs. A wide range of geologic formations can host aquifers, including sand, gravel, limestone, sandstone, or fractured igneous rocks. Permeability is a measure of how well a material can transmit water. Aquifer materials like gravel transmit water quickly and have high permeability. Aquifer materials like cemented sandstone transmit water more slowly and have lower permeability. Materials such as shales are typically classified as aquitards, or formations that restrict water movement, and have low permeability.

Some of the largest aquifers in Texas, including the Ogallala, Gulf Coast, and Carrizo-Wilcox aquifers, consist of sedimentary rocks with intergranular porosity and relatively high permeability. Limestone aquifers, such as the Edwards (Balcones Fault Zone) Aquifer, contain water in crevices and caverns caused mainly by the dissolution of limestone by groundwater. The Igneous Aquifer in West Texas is an example of an aquifer where groundwater flows through cracks, fractures, and joints developed in igneous and volcanic rocks.

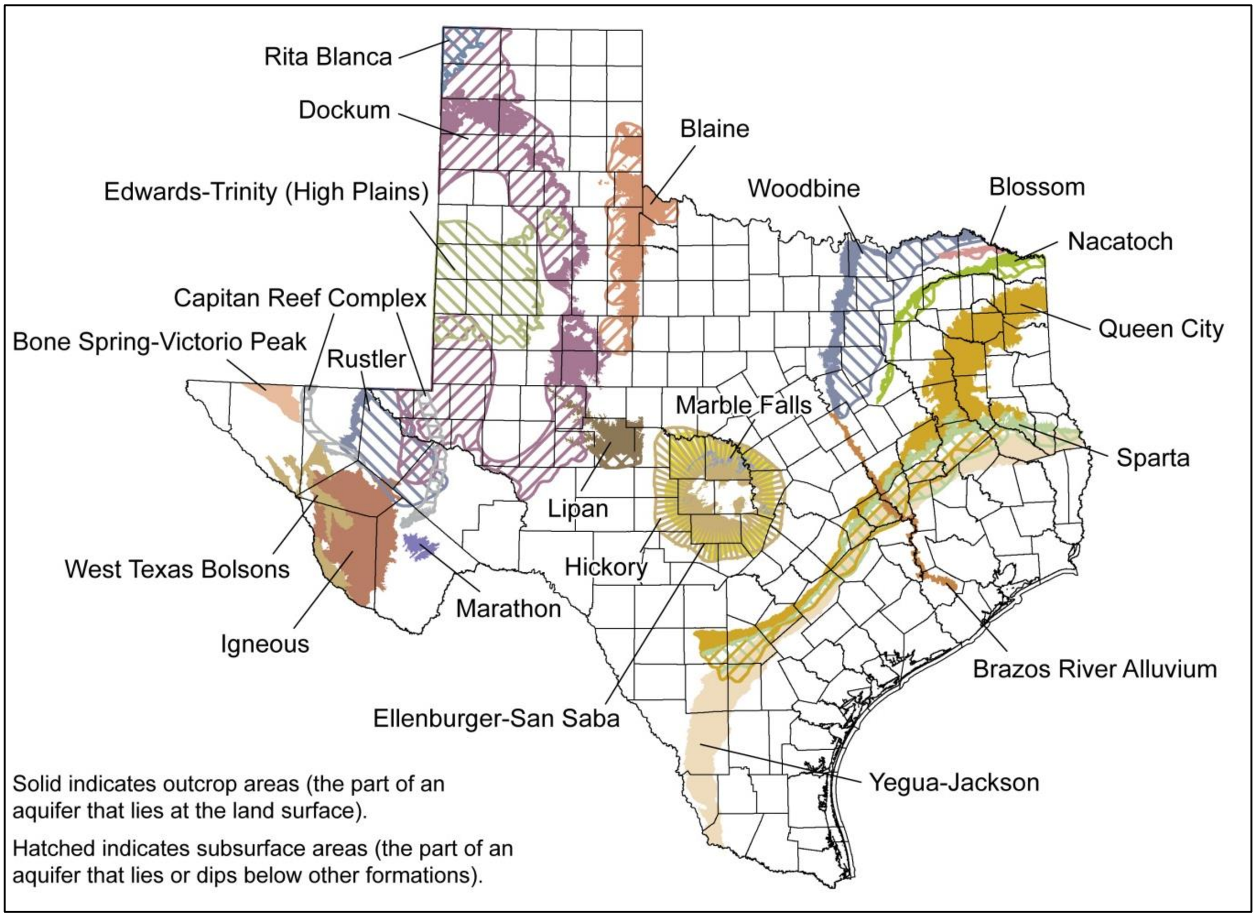


Figure 1-2. The minor aquifers of Texas.

The TWDB classifies Texas aquifers as confined (subsurface) or unconfined (outcrop). Confined and unconfined aquifers respond differently to pumping and other surface processes (Figure 1-3).

Unconfined aquifers are sometimes referred to as "water table aquifers" and occur in the outcrop area of the aquifer. An unconfined aquifer is one in which the water table is at or near atmospheric pressure and is the upper boundary of the aquifer. Because the aquifer is not under pressure, the water level in a well is the same as the water table outside the well (left side of Figure 1-3). Water levels in a well completed in an unconfined aquifer rise and fall in response to changes in recharge and discharge. When water levels decline, water physically drains from the aquifer. The specific yield of unconfined aquifers, or the volume of water produced per unit decline in water level, is typically close to the effective porosity and can range from 0.05 to 0.35 for sedimentary aquifers, depending on the aquifer material.

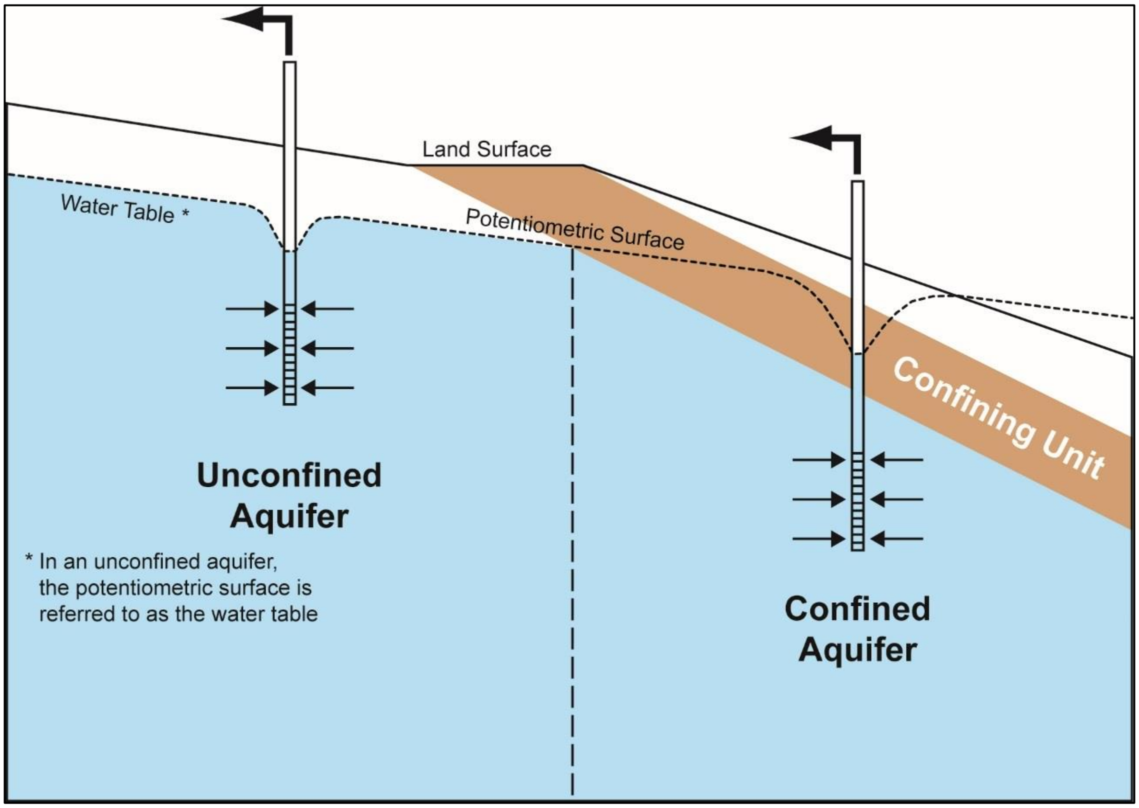


Figure 1-3. Schematic cross-section of an aquifer with unconfined and confined portions.

Confined aquifers are sometimes referred to as “artesian aquifers.” These aquifers are overlain by confining units, such as clay and shale layers, that do not readily transmit groundwater (right side of Figure 1-3). These aquifers usually occur well below the land surface, are completely saturated with groundwater, and are under pressure. Because of this pressure, water in wells penetrating confined aquifers rises above the top of the aquifer. In some cases, water levels may rise above the land surface, resulting in a flowing well. The level to which water rises in a confined aquifer is the potentiometric surface of the confined aquifer. Pumping from wells reduces the water pressure in the aquifer and lowers the potentiometric surface in a “cone of depression” around the well, even though the aquifer remains fully saturated.

Groundwater storage in confined aquifers consists of two parts, the storativity and specific yield. The storativity represents the groundwater released from confined storage while the aquifer remains fully saturated. The specific yield represents groundwater released from the aquifer if the water level is drawn down below the top of the aquifer, at which point it becomes unconfined. The storativity is typically much smaller than the specific yield, ranging from 0.005 to 0.00005. Large decreases in the potentiometric surface over extensive areas typically are required to produce substantial quantities of water from confined aquifers; the total volume of the cone of depression in a typical confined aquifer is about 2,000 times larger than the total volume of the cone of depression in a typical unconfined aquifer (Alley and others, 1999).

The major and minor aquifers of Texas include both confined and unconfined systems. In many cases, a single aquifer system consists of both confined and unconfined portions. The Ogallala and Seymour aquifers are unconfined throughout; with a specific yield around 0.15, they can produce large volumes of water per unit area. The Gulf Coast Aquifer is also classified as unconfined in the outcrop area, where it is characterized by a shallow groundwater flow system. This aquifer has a complex structure of interlayered sand, silt, and clay strata that can result in a much lower specific yield, particularly in the deeper regional flow environment where confined conditions predominate. The Carrizo-Wilcox and Trinity aquifers are examples of systems that include both confined and unconfined portions. These aquifers are unconfined where they outcrop and are exposed at the ground surface but become confined in deeper zones where permeable strata extend below clay and shale formations.

1.4 Tributary and non-tributary aquifers

Although Texas water law does not define the meaning of tributary aquifer, the term has been applied in a number of court cases across the nation. In general, a tributary aquifer is an aquifer that has groundwater that discharges to surface water. Conversely, non-tributary aquifers do not discharge groundwater to surface water. Groundwater that is isolated from other aquifers and surface water is designated as non-tributary. Quatrochi (1996) uses these concepts in the context of the Clean Water Act definition of waters of the United States.

The concept of tributary aquifers is also used in the context of water management by the State of Colorado. Colorado considers that if groundwater production diminishes surface-water flows at an annual rate greater than one-tenth of 1 percent of the annual rate of groundwater withdrawal within 100 years, then the groundwater is considered tributary. Groundwater that is isolated from other aquifers and surface water is designated as non-tributary (Colorado Department of Natural Resources, 2016). Direct use of the Colorado definition for tributary groundwater is not necessarily appropriate for Texas because these terms are applied within a legal context entirely different from the water law in Texas. Additionally, the Colorado law is used to define administrative zones within an aquifer rather than to classify entire aquifers as tributary or non-tributary. As in Colorado, most aquifers in Texas include both unconfined outcrop zones, where the aquifer interacts with surface rivers and streams, and confined zones, where the aquifer is more or less separated from surface flows by less permeable formations.

Groundwater and surface-water interactions also vary over time, further complicating delineation of tributary zones. The normal seasonal cycles of recharge and discharge and longer term groundwater responses to drought and flooding affect groundwater and surface-water relationships. For example, groundwater production for municipal, industrial, and agricultural purposes has resulted in water-level declines in many Texas aquifers, such that springflows and groundwater contributions to surface water in general are greatly reduced from pre-development volumes.

Finally, the volume of groundwater discharge that is "enough to directly and significantly affect that body of water, stream, or river" depends on the total volume of flow in the surface-water body. In western parts of Texas perennial water sources are scarce, and even relatively small springs and seeps may be important resources for landowners and wildlife.

In Oklahoma, conflict between surface-water and groundwater rights led to litigation over management of the Arbuckle-Simpson Aquifer, although the term "tributary aquifer" was not specifically applied. Oklahoma's Senate Bill 288, passed in 2003, imposed a moratorium on issuing groundwater permits for certain uses of the Arbuckle-Simpson Aquifer until the Oklahoma Water Resources Board approved maximum annual yield limits that do not reduce flow in springs and streams (Oklahoma Water Resources Board, 2003). The hydrological study to define the maximum annual yield limits took a decade to complete. In 2013 the Oklahoma Water Resources Board ruled that the maximum annual yield of the aquifer was 2.4 acre-inches per acre per year, which represents only about 10 percent of 2.0 acre-feet per acre per year of groundwater use previously allowed (Oklahoma Water Resources Board, 2013). The final maximum annual yield was contested as a "taking" by a group of affected landowners. The 2013 ruling was upheld on appeal in 2015 (State Impact Oklahoma, 2015).

In summary, there are a number of complicating factors when considering the question of tributary and non-tributary aquifers. This study is statewide in scope and evaluates the tributary groundwater conditions on a regional scale. Detailed analyses of groundwater and surface-water interactions will be required to address specific local questions of whether or not groundwater may be tributary in character.

2 Quantity and Quality of Groundwater in Confined and Unconfined Aquifers

The usability of groundwater resources depends on the quantity and quality of the water contained in each aquifer as well as the needs of users. The total recoverable storage in the saturated pore space of aquifers gives a snapshot of the quantity of groundwater in Texas, like the balance in a bank account, but doesn't address the effects or the economic viability of draining aquifers. Changes in groundwater quantity over time, reflected in water-level changes, give an indication of how we are managing the available resources. Water quality issues can also affect the production and use of groundwater. This section evaluates TWDB data on the quantity and quality of water in the confined and unconfined aquifers of Texas. A separate TWDB report to the legislature describes brackish groundwater resources outside the established areas of officially named aquifers.

2.1 Groundwater quantity

Key points:

- Confined and unconfined major and minor aquifers contain an estimated 16.8 billion acre-feet of fresh and brackish groundwater.
- Groundwater storage in confined aquifers consists of water stored under pressure in the saturated system (confined groundwater) plus water released as the aquifer physically drains under atmospheric pressure (unconfined groundwater). The amount of groundwater that can be produced before the aquifer starts to desaturate is very small compared to the total amount of water stored—probably much less than 1 percent of the total storage volume.
- The annual volume of groundwater pumped in Texas peaked in the 1970s and has been relatively stable for the past 20 years. Annual groundwater pumping is between approximately 8 and 10 million acre-feet per year.
- Large areas of some Texas aquifers have experienced drawdown of water levels over the past 20 years. The Hueco-Mesilla Bolsons, portions of the Ogallala, the northern Trinity, the northern Carrizo-Wilcox, and portions of the Gulf Coast aquifers have experienced consistent declines.
- Rising water levels in the Houston area are a result of reduced groundwater pumping to mitigate land subsidence.
- Emerging areas of drawdown are seen in the Ogallala Aquifer in the Pampa area (Roberts County) and in the Carrizo-Wilcox Aquifer south and west of San Antonio.

For this study, the quantity of groundwater in the state's unconfined and confined aquifers is expressed in terms of how much groundwater is physically present in the aquifers. This is in contrast to groundwater supply or availability, which represents the estimated amount of groundwater that can be withdrawn or is accessible as a result of policy decisions and management directives. For groundwater supply and availability estimates, please refer to the 2017 State Water Plan (TWDB, 2016), which includes estimates developed through joint planning efforts by groundwater conservation district representatives and regional water planning groups, and the study by Hermitte and others (2015), comparing groundwater availability estimates with the desired future conditions developed by groundwater management areas.

The quantity of groundwater in Texas aquifers can be estimated in a number of ways. For the purposes of this study, the TWDB defines quantity in terms of the 'total estimated recoverable storage'. We used this approach for two reasons:

1. the Texas Legislature in 2011 identified the concept of total estimated recoverable storage as a factor in statewide joint planning activities for groundwater management, and
2. the TWDB has calculated total estimated recoverable storage for almost all of the major and minor aquifers of the state and reported these estimates to groundwater conservation districts.

Total estimated recoverable storage

Total estimated recoverable storage values represent point-in-time, static estimates of the groundwater volume present in Texas aquifers and do not account for dynamic aspects of groundwater systems such as recharge and natural discharge. The total estimated recoverable storage values do not consider possible effects of groundwater withdrawals, including degradation of water quality, subsidence, dewatering of an aquifer, or other effects.

The total volume of recoverable groundwater in storage within the defined boundaries of the major and minor aquifers is estimated to be between 4.2 and 12.6 billion acre-feet (Table 2-1). Texas aquifers range from those that are entirely freshwater aquifers, to those with both fresh and brackish aquifers, and to some that are entirely brackish. Groundwater storage in brackish systems outside the delineated aquifer boundaries is the subject of a separate TWDB report to the Texas Legislature to be delivered by December 31, 2016.

Groundwater storage is dominated by the Gulf Coast and Carrizo-Wilcox aquifers, which together account for almost two-thirds of the groundwater in storage in Texas. Much of the groundwater in these aquifers may not be readily recoverable because of the excessive depth to the base of the aquifer in parts of the confined area or may not be economically viable at this time due to the occurrence of poor-quality groundwater at depth.

Although more groundwater is pumped from the Ogallala Aquifer than all other aquifers combined, the total recoverable storage remaining in this aquifer amounts to only 95.3 million to 286 million acre-feet, or just over 2 percent of the total groundwater in storage in Texas. Groundwater in the Ogallala Aquifer is being withdrawn at a rate roughly equivalent to 2 to 5 percent of the total recoverable storage per year.

Table 2-1. Total estimated recoverable groundwater storage in Texas aquifers[1].

Aquifer	25% of total storage (acre-feet)	75% of total storage (acre-feet)	Remarks
Major Aquifers			
Carrizo-Wilcox	1,310,000,000	3,920,000,000	Includes brackish water in deep confined portions of aquifer
Edwards (Balcones Fault Zone)	6,250,000	18,800,000	Storage estimates are very sensitive to the rapid recharge and discharge characteristics of aquifer
Edwards-Trinity (Plateau)	11,400,000	34,100,000	
Gulf Coast	1,300,000,000	3,890,000,000	Includes brackish water in deep confined portions of aquifer
Hueco-Mesilla Bolsons[2]	2,250,000	6,750,000	Freshwater portion of aquifer
Ogallala	95,300,000	286,000,000	Unconfined aquifer
Pecos Valley	81,000,000	243,000,000	Includes fresh and brackish groundwater
Seymour	1,280,000	3,850,000	Groundwater is seasonally depleted and recharged
Trinity	353,000,000	1,060,000,000	Includes brackish water in deep confined portions of aquifer
Minor Aquifers			
Blaine	43,000,000	129,000,000	Predominantly brackish groundwater.
Blossom	1,770,000	5,310,000	
Bone Spring-Victorio Peak	925,000	2,780,000	
Brazos River Alluvium	803,000	2,410,000	
Capitan Reef Complex	13,800,000	41,300,000	
Dockum	373,000,000	1,120,000,000	Predominantly brackish groundwater.
Edwards-Trinity (High Plains)	5,930,000	17,800,000	
Ellenburger-San Saba	21,800,000	65,250,000	
Hickory	16,600,000	49,700,000	
Igneous	16,000,000	48,100,000	
Lipan	1,050,000	3,150,000	
Marathon	375,000	1,130,000	
Marble Falls	66,300	199,000	
Nacatoch	1,020,000	3,070,000	
Queen City	135,000,000	404,000,000	Includes brackish water in deep confined portions of aquifer.
Rita Blanca	2,780,000	8,330,000	
Rustler	9,230,000	27,700,000	
Sparta	46,500,000	140,000,000	Includes brackish water in deep confined portions of aquifer.
West Texas Bolsons	12,900,000	38,600,000	
Woodbine	56,800,000	170,000,000	Includes brackish water in deep confined portions of aquifer.
Yegua-Jackson	300,000,000	900,000,000	Includes brackish water in deep confined portions of aquifer.

Notes:

[1] Aquifer storage properties and geometries in approved groundwater availability models are used to calculate total estimated recoverable storage. Values for individual aquifers are rounded to three significant figures.

[2] Value from Bredehoeft and others (2004); the TWDB has not established total estimated recoverable storage values for the Hueco-Mesilla Bolsons Aquifer.

2.2 Water-level changes

Key points:

- Groundwater levels in all major and minor aquifers have declined.
- Some groundwater declines have been reversed locally as pumping patterns change (Houston area) or recharge exceeds discharge (portions of the Ogallala Aquifer and the Edwards [Balcones Fault Zone] Aquifer).

Water-level changes over time reveal the responses of Texas aquifers to recharge and discharge conditions. Since 1895 over one million groundwater levels have been measured and recorded in Texas aquifers. Every year, an estimated 8,600 wells representing every county in Texas and every major and minor aquifer are monitored by the TWDB, cooperating groundwater conservation districts, and the U.S. Geological Survey. These data form much of the basis for evaluating the condition of Texas aquifers.

Figure 2-1 illustrates water-level changes derived from groundwater availability model estimates of changes in water levels between recently calibrated years (generally around the year 2000) and water levels in pre-development (pre-pumping) years. Water-level declines in the eastern part of the state tend to be declines in artesian pressure, whereas water-level declines in the western part of the state tend to be declines in the water table. Total water-level declines in the state’s aquifers since 1900 range from less than 50 feet to more than 1,000 feet. The greatest water-level declines are in the Trinity Aquifer, focused in the Dallas–Fort Worth and Waco areas. One hundred years ago, wells in much of the Trinity Aquifer flowed at the surface, releasing so much artesian pressure that most ceased to flow by the mid-1910s. For example, a well screened in the lower Trinity Aquifer in Austin initially “threw water 40 feet high” (Brune, 1975). Other areas of large water-level declines are in the Carrizo-Wilcox Aquifer in the Winter Garden irrigation area north of Laredo; near Lufkin, Nacogdoches, and Tyler; and in the Gulf Coast Aquifer near Houston. Water levels in parts of the Ogallala Aquifer, an unconfined aquifer, have also declined more than 300 feet. All of these water-level declines have been caused by groundwater pumping, primarily since the 1950s. Figure 2-2 tracks the total groundwater pumping in Texas from 1937 to 2013, as estimated by the TWDB and the U.S. Geological Survey (USGS, 1950 to 2010).

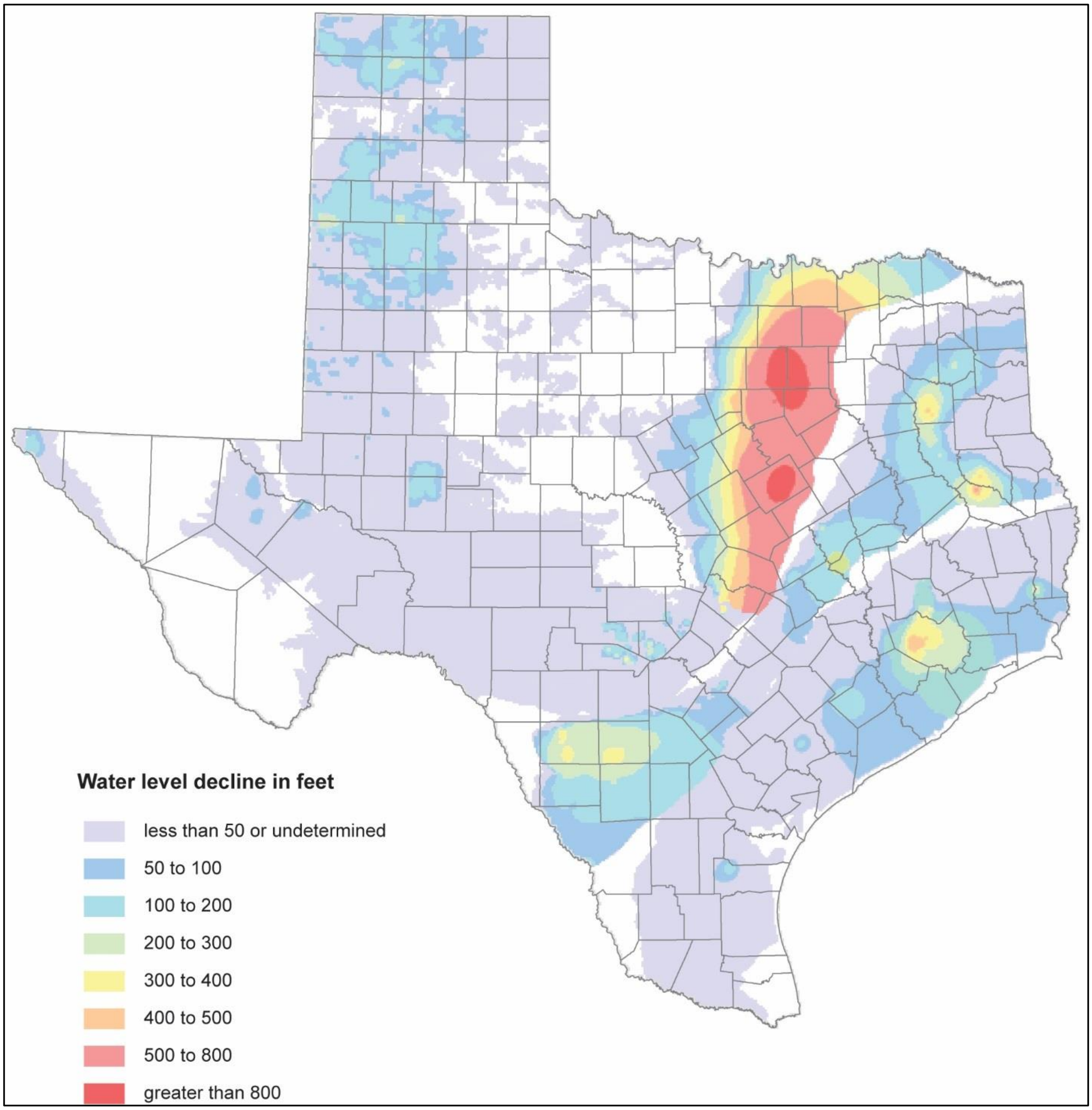


Figure 2-1. Estimated total water-level declines in the major aquifers of Texas.

For this study, we also considered a series of groundwater level measurements over the last 20 years—using data from between 3,786 and 4,606 wells—in five-year intervals beginning in 1995. We calculated the difference between the minimum depth to groundwater measured during the non-pumping season at the beginning and end of each period in each well and then used geostatistical interpolation (with default kriging parameters in ArcGIS 10.3) to generate a map of water-level changes across the areas of all major aquifers in Texas.

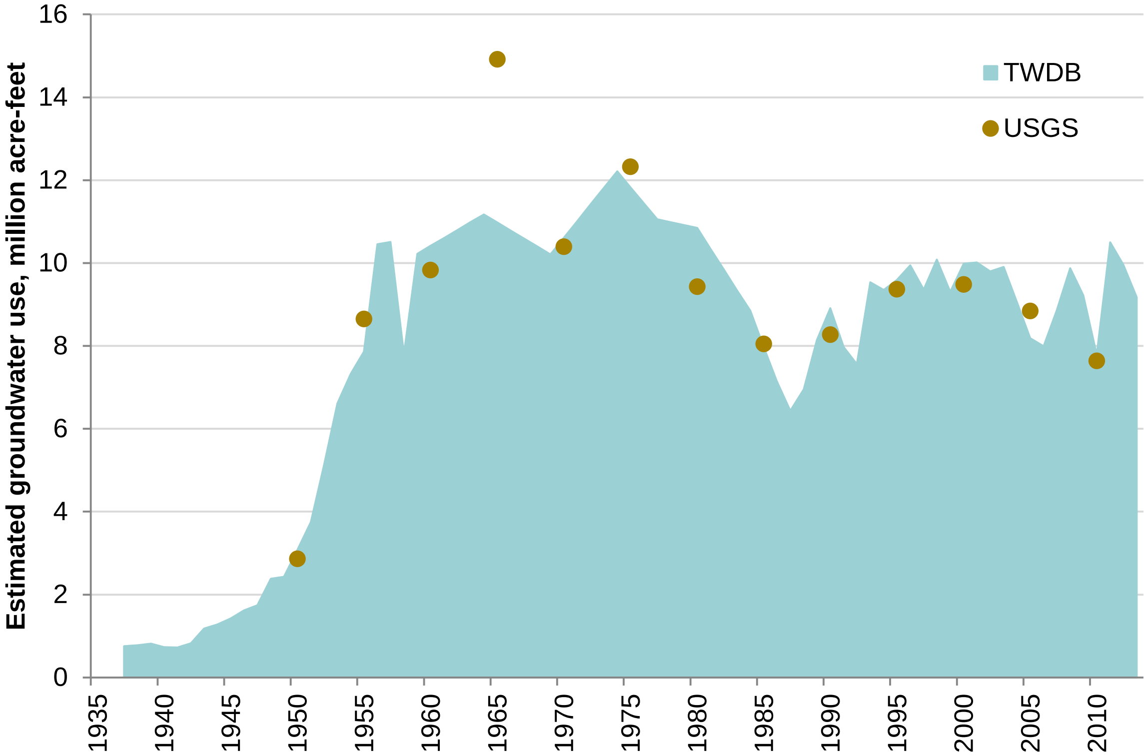


Figure 2-2. **Estimated total annual groundwater use in Texas, in millions of acre-feet.**

Figure 2-3 shows four maps of groundwater-level changes from 1995 to 2015. These maps show the dynamic nature of groundwater conditions, illustrating several areas where there have been significant groundwater-level increases or decreases. Consistent water-level declines occurred in several areas, including

- portions of the Ogallala Aquifer with active irrigation (Dallam and Hartley counties; Parmer, Castro, Lamb, and Hale counties; Gaines and Dawson counties);
- the Trinity Aquifer in the Dallas-Fort Worth and Waco areas;
- the Gulf Coast Aquifer north of Houston; and
- the southern Carrizo-Wilcox, where large-scale oil-field development has taken place since 2005.

Most wells show moderate drawdown over the 20-year period. The median drawdowns for all aquifers except the Edwards (Balcones Fault Zone) and Trinity aquifers are less than 10 feet over 5 years. Areas of greater drawdown are generally localized in the vicinity of municipal water supply well fields. The relatively large drawdowns in the Edwards (Balcones Fault Zone) and Trinity aquifers also reflect the unique hydrologic properties of these aquifers, specifically the low storage coefficients for the confined portions of these aquifers, which result in larger drawdown for a given volume of pumping, relative to unconfined systems.

Areas of increased water levels between 2000 and 2005 are likely the result of reduced demand and recharge from major storm events to the Edwards (Balcones Fault Zone) Aquifer and other aquifers in South and Central Texas. For example, in July 2002 a large area of Central Texas received 34 inches of rain in about a week.

In contrast, from 2010 to 2015 the state experienced significant drought. This led to widespread increases in groundwater use as surface-water supplies were diminished. Every aquifer experienced decreasing groundwater levels in this five-year period, with the exception of some areas in the Gulf Coast Aquifer, where pumping limits to mitigate subsidence have been in place for 40 years.

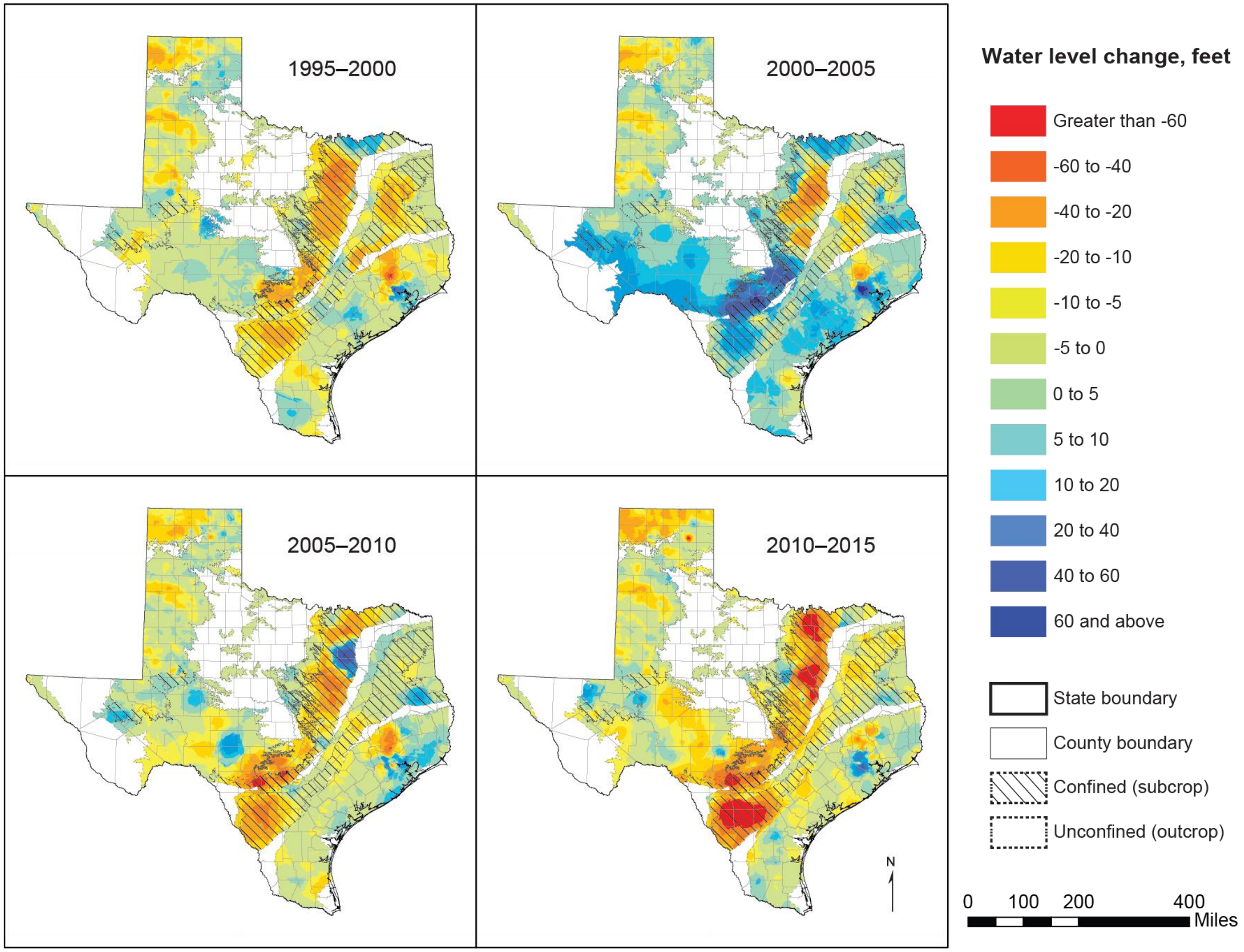


Figure 2-3. **Water-level changes measured by the TWDB monitoring program in individual wells completed in major and minor aquifers in Texas, 1995 through 2015.**

2.3 Groundwater quality

Key points:

- Most groundwater in major and minor aquifers is fresh. The total dissolved solids content of groundwater in these aquifers is mostly less than 1,000 milligrams per liter.
- The official boundaries of many of the aquifers are determined based on water quality zonation; the water-bearing formation may continue beyond an aquifer boundary but contains more saline water.
- Areas of the southern Ogallala, the Pecos Valley, the Seymour, and the southern Gulf Coast aquifers and the down-dip confined areas of the Trinity and Carrizo-Wilcox aquifers are brackish.
- Groundwater quality in minor aquifers is more variable. Areas of brackish groundwater are present in most of the minor aquifers.
- Groundwater quality reflects complex interactions between water and the geologic formation. Research on the geochemical effects of recharge and changing hydraulic gradients is part of the TWDB groundwater quality monitoring program.

Groundwater quality—expressed as salinity or total dissolved solids concentrations—has been studied extensively in the state's major and minor aquifers. The TWDB collects water samples from wells and springs in major and minor aquifers throughout the state as part of its ambient groundwater quality monitoring program. These samples are analyzed by an accredited lab to provide data to characterize the natural quality of groundwater in aquifers and any changes that may have occurred over time. Over a four-year sampling period, the TWDB collects or obtains—from samples collected by cooperators—analyses of up to 1,300 groundwater quality samples. No significant changes in water quality have been detected in groundwater from wells sampled by the TWDB and its cooperators, although evaluation is ongoing.

Groundwater quality is classified by the U.S. Geological Survey and the TWDB according to salinity (total dissolved solids) and the following criteria:

- Fresh–total dissolved solids concentrations less than 1,000 milligrams per liter
- Brackish–total dissolved solids concentrations between 1,000 and 10,000 milligrams per liter
- Saline–total dissolved solids concentrations greater than 10,000 milligrams per liter

The TWDB Brackish Aquifer Characterization System further subdivides brackish groundwater into slightly saline (total dissolved solids concentrations between 1,000 and 2,999 milligrams per liter) and moderately saline (total dissolved solids concentrations between 3,000 and 9,999 milligrams per liter) categories.

The total dissolved solids content of groundwater affects its usability for different purposes. Total dissolved solids are a measure of the salinity of water and represent the amount of minerals dissolved in water, generally reported as milligrams per liter of water. If water is too saline, then it may not be drinkable without treatment or it may not be suitable for irrigation. Water with total dissolved solids less than 1,000 milligrams per liter is considered fresh and is generally usable. Water with total dissolved solids of as much as 1,500 milligrams per liter may be used to irrigate crops, depending on the type of crop and the levels of other dissolved constituents in the water. Water with total dissolved solids as high as 3,000 milligrams per liter may still be used for livestock. Water with total dissolved solids between 1,000 and 10,000 milligrams per liter, also called brackish groundwater, is a potential source of water for desalination.

We mapped the total dissolved solids content of Texas groundwater using analytical results from the TWDB database for water samples from wells completed in all major aquifers. Several groundwater conservation districts and the U.S. Geological Survey provided additional data. Older data were not excluded from our evaluation as analytical methods for total dissolved solids have not changed significantly over time and are generally reliable. Where more than one value was listed for a particular well, only the latest value was used. We used a total of almost 40,000 data points to map the distribution of total dissolved solids across the state. Sample counts per aquifer ranged from over 9,000 data points in the Gulf Coast Aquifer to just over 600 data points in the Hueco-Mesilla Bolsons Aquifer. We used ArcGIS 10.3 to interpolate the data using ordinary kriging and plotted the results over the area covered by the major aquifers (Figure 2-4).

Much of the water in the state’s aquifers is fresh; however, brackish groundwater is more common than fresh groundwater in the southern Gulf Coast area and in large parts of west Texas. The confined portions of many aquifers become more saline down-dip (deeper in the aquifer) as a result of limited circulation and interaction with aquifer materials, in particular with evaporitic minerals that are present deeper in the geological section in many of the sedimentary basins of Texas. Our map of total dissolved solids is limited to officially-defined areas of the major aquifers and does not show the full down-dip extent of the water-bearing formations.

Although the vast majority of groundwater used for drinking in Texas meets state and federal requirements for safety, in some parts of the state naturally occurring levels of total dissolved solids, arsenic, and radionuclides, as well as human-caused nitrate contamination, prevent the water from meeting those standards. A TWDB study by Reedy and others (2011) documented the distribution of these naturally occurring contaminants in Texas groundwater. We discuss these water quality issues in the aquifer summaries presented in Chapter 6 of this report.

Localized areas of anthropogenic contamination are also present in Texas groundwater as a result of commercial, industrial, and agricultural activities. A 2011 TWDB study of groundwater in the vicinity of potential sources of contamination detected the herbicides atrazine and its metabolites, simazine, and prometon as well as the chlorinated compounds tetrachloroethylene, a dry-cleaning product, and chloroform, a common public water supply disinfection byproduct, in over 10 percent of the groundwater samples tested. Most of these detections were at concentrations below the laboratory's practical quantitation limits, and only two, tetrachloroethylene and atrazine, had greater than 1 percent of detections above the practical quantitation limits (O'Rourke and others, 2011). The Texas Commission on Environmental Quality also publishes an annual report on the quality of groundwater in Texas, listing all current groundwater contamination cases in the state and their enforcement status (TCEQ, 2015). Our study does not attempt to address specific instances of groundwater contamination at regulated facilities.

Finally, the TWDB has conducted extensive geochemical investigations of Texas groundwater to support the groundwater availability modeling program (Scanlon and others, 2011; Kreitler and others, 2013a; Kreitler and others 2013b; Young and others, 2014). The chemical and isotopic composition of groundwater serves as a powerful tool for understanding the natural recharge, flow, and reaction pathways in Texas aquifers.

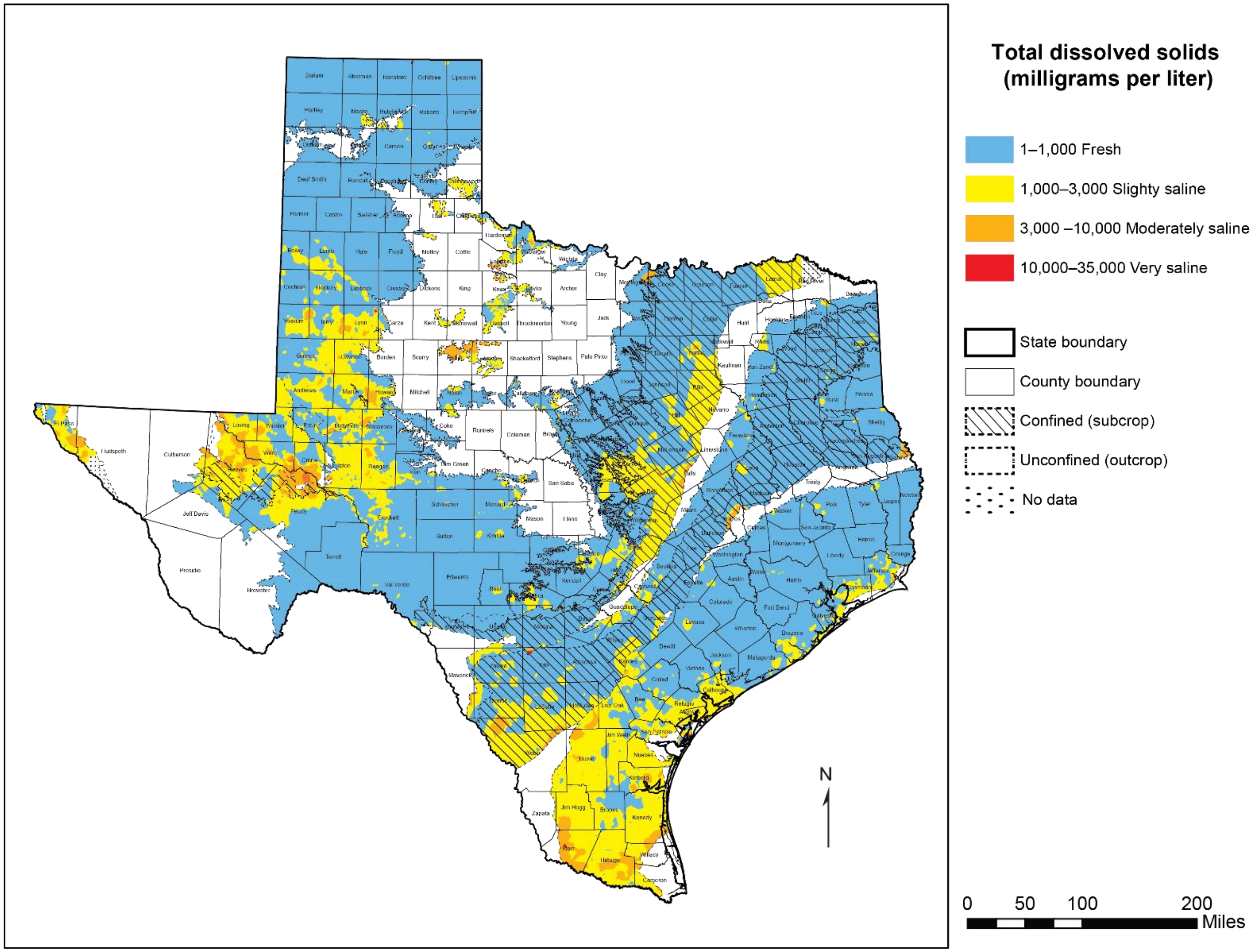


Figure 2-4. Concentration of total dissolved solids in wells sampled by TWDB and other cooperators through 2015.

3 Groundwater and Surface-water Interactions

Key points:

- All aquifers contribute some groundwater to the baseflow of streams and rivers in Texas.
- An estimated 9.3 million acre-feet of groundwater flows from major and minor aquifers to surface water in an average year. This represents about 30 percent of the average surface-water flow in Texas.
- Aquifer interactions with surface water vary regionally and within each aquifer. Between 14 and 72 percent of streamflow over aquifer outcrop areas is due to groundwater discharge from major and minor aquifers.
- The largest groundwater contributions to surface water occur in East Texas, the Hill Country, and around major springs in West Texas.
- The aquifer with the most groundwater discharge to surface water is the Gulf Coast Aquifer, with an estimated 3.8 million acre-feet per year.
- About half of Texas aquifers contribute less than 50,000 acre-feet per year to surface-water flows.

3.1 Background

Groundwater and surface-water interactions have been an area of interest for decades. Observations of groundwater and surface-water interaction originally focused on springflow; TWDB Report 189 (Brune, 1975) documents the major and historical springs of Texas. When the document was published, it was estimated that 3 million acre-feet per year flowed from Texas aquifers to surface water through large and small springs. Nearly half of the documented large springs were associated with two major aquifers: the Edwards (Balcones Fault Zone) Aquifer and the Edwards-Trinity (Plateau) Aquifer. The counties with the most springs classified as large were San Saba, Val Verde, and Kerr counties. Figure 3-1 shows the location of springs in the TWDB Groundwater Database along with the major aquifers in Texas, based on data from Heitmuller and Reece (2013). But groundwater and surface-water interactions involve much more than observable springs. The most difficult aspect of groundwater and surface-water interaction is quantifying the relationships along stretches of streams and rivers where diffuse groundwater flow contributes to or originates as aquifer recharge from surface water. In these cases, direct measurements and observations are problematic. Furthermore, seasonal changes in the magnitude and direction of groundwater and surface-water interactions confound efforts to quantify the interactions on a statewide level.

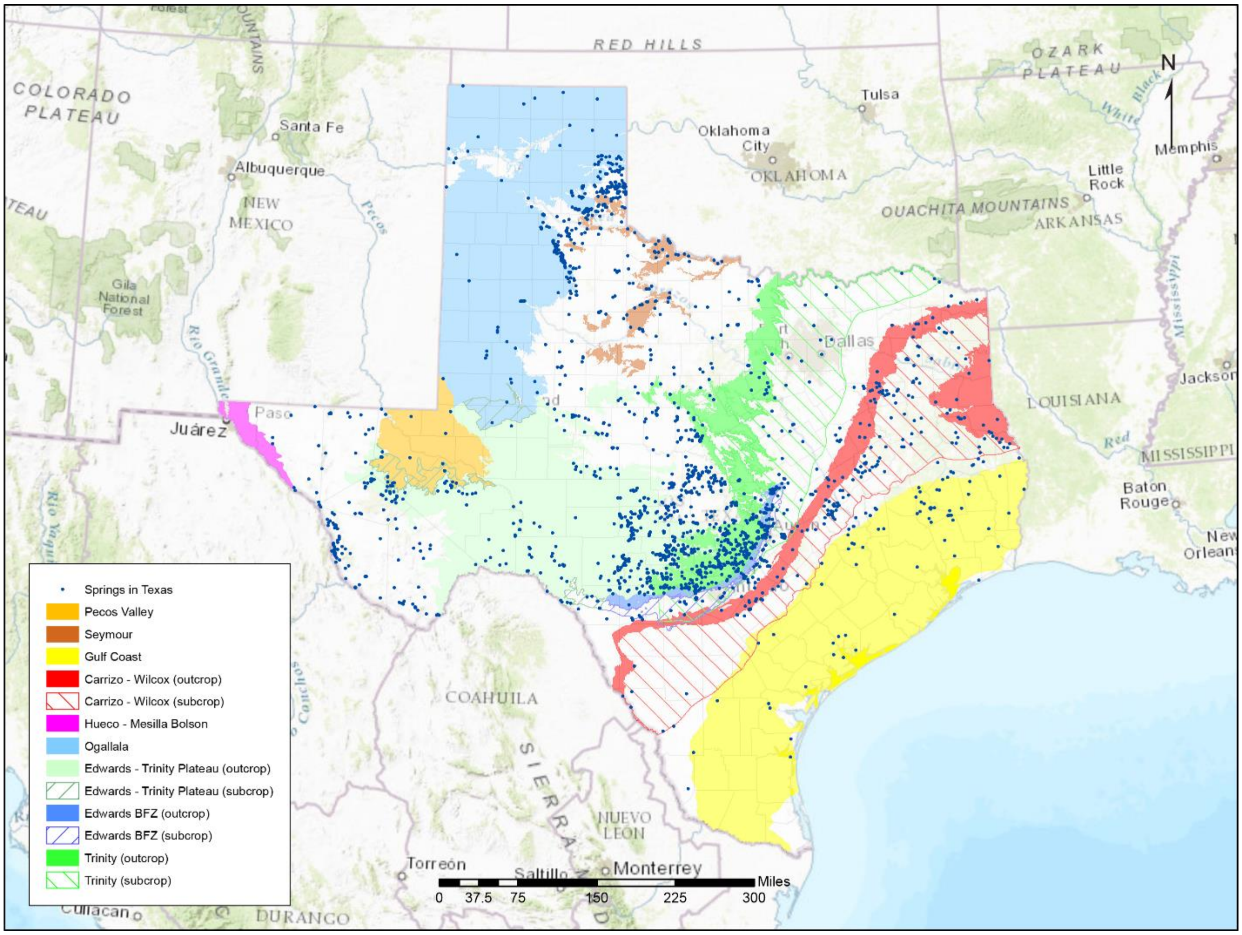


Figure 3-1. **Location of springs in Texas and the major aquifers of Texas (data from Heitmuller and Reece, 2013).**

A number of research projects on the topic have been conducted in recent decades, several of which have been funded by either the TCEQ or the TWDB. Parsons (1999) provides a descriptive statewide review of groundwater interaction in the major river basins; a qualitative summary is provided in Table 3-1. Scanlon and others (2005) compiled an extensive list of references on the general topic of groundwater and surface-water relationships, with particular focus on Texas. That study also examined techniques to quantify groundwater and surface-water interactions at the watershed scale in terms of both water flow and water quality. Detailed characterization of groundwater and surface-water interactions at the scale of entire river basins or aquifers remains incomplete.

Table 3-1. **Summary of groundwater and surface-water interactions in the river basins of Texas.[1]**

River Basin	Aquifers	Groundwater and surface-water interaction	Degree/direction of interaction
Brazos-Colorado Coastal Basin	Gulf Coast	Aquifer generally contributes to streams	Variable
Canadian River	Ogallala	Aquifer generally contributes to streams	Variable
Colorado River	Llano Uplift aquifers, Edwards-Trinity (Plateau), Trinity, Carrizo-Wilcox, Gulf Coast	Groundwater discharges to streams; surface water recharges groundwater	Large river basin has variable interaction due to geologic and climate variations
Colorado-Lavaca Coastal Basin	Gulf Coast	Aquifer generally contributes to streams	Variable
Cypress Creek	Carrizo-Wilcox, Queen City	Groundwater discharges to streams; surface water recharges groundwater	Variable (and generally diffuse) distribution of interactions
Guadalupe River	Edwards-Trinity (Plateau), Trinity, Edwards, Carrizo-Wilcox, Gulf Coast	Aquifer generally contributes to streams	Variable
Lavaca River	Gulf Coast	Aquifer generally contributes to streams	Variable
Lavaca-Guadalupe Coastal Basin	Gulf Coast	Aquifer generally contributes to streams	Variable
Neches River	Carrizo-Wilcox, Queen City, Sparta, Gulf Coast	Aquifers generally contribute to streams	
Neches-Trinity Coastal Basin	Gulf Coast	Aquifer generally contributes to streams	
Nueces River	Edwards-Trinity (Plateau), Trinity, Edwards, Carrizo-Wilcox, Queen City, Sparta, Gulf Coast	Aquifers generally contribute to streams with some surface water recharge of aquifer in some locations	Variable
Nueces-Rio Grande River Basin	Gulf Coast	Aquifer generally contributes to streams	Variable

Table 3-1 (continued). Summary of groundwater and surface-water interactions in the river basins of Texas.[1]

River Basin	Aquifers	Groundwater and surface-water interaction	Degree/direction of interaction
Red River	Ogallala, Seymour	Aquifers generally contribute to streams	Seasonal variability
Sabine River	Carrizo-Wilcox, Nacatoch, Queen City, Gulf Coast	Groundwater discharges to streams; surface water recharges groundwater	
San Antonio River	Edwards-Trinity (Plateau), Trinity, Edwards, Carrizo-Wilcox	Aquifers generally contribute to streams with some surface water recharge of aquifer in some locations	Variable
San Antonio-Nueces Coastal Basin	Gulf Coast	Aquifer generally contributes to streams	Variable
San Jacinto River	Gulf Coast	Aquifer generally contributes to streams	Variable
San Jacinto-Brazos Coastal Basin	Gulf Coast	Aquifer generally contributes to streams	Variable
Sulphur River	Trinity, Woodbine, Carrizo-Wilcox	Streams contribute to Trinity and Woodbine aquifers; Carrizo-Wilcox Aquifer discharges to streams	Variable (and generally diffuse) distribution of interactions
Trinity River	Trinity, Woodbine, Nacatoch, Carrizo-Wilcox, Queen City, Sparta	Groundwater discharges to streams; surface water recharges groundwater	Large river basin has variable interaction due to geologic and climate variations
Trinity-San Jacinto Coastal Basin	Gulf Coast	Aquifer generally contributes to streams	

[1] Information in table summarized from Parsons (1999).

3.2 Study approach

House Bill 1232 directed the TWDB to determine the contributions of groundwater from major and minor aquifers to surface water in the state of Texas and to produce a map of these contributions. As noted above, there are numerous studies of groundwater and surface-water interactions but none provide a quantitative evaluation of groundwater contributions from all major and minor aquifers. We evaluated several possible technical approaches for this evaluation but chose to use a statewide baseflow analysis to determine the contributions of groundwater flows to surface water with consistent scale and conceptualization across the state. Although the TWDB groundwater availability models are capable of calculating groundwater flows to surface-water bodies, we decided not to use these models for this purpose since they are generally not appropriately scaled, conceptualized, or calibrated to model groundwater and surface-water interactions.

For this study, baseflow is defined as the component of sustained natural streamflow in the absence of direct runoff from precipitation and attributed specifically to natural groundwater discharge from the underlying outcrops of major and minor aquifers. Estimates of baseflow are conceptualized as the positive net flow of groundwater to surface water in excess of any surface-water losses to the underlying aquifer(s). The hydrologic process of groundwater discharge into surface water is assumed to occur naturally through stream beds and/or through seeps and springs contributing directly to a surface-water body or its tributaries within a surface-water drainage basin.

The U.S. Geological Survey has compiled a geospatial dataset of annual flow and basin characteristics for stream gages in the 48 contiguous states, including 599 locations in Texas (Wolock, 2003a). The annual flow data include the average annual streamflow and the average annual baseflow index (Wolock, 2003a). The basin characteristics used for this study include the watershed drainage area and the hydrologic landscape region associated with each of the stream gages. The baseflow index is the fraction of the average annual streamflow attributed to baseflow for periods of record representing unregulated streamflow at each site. The baseflow indices were computed by the U.S. Geological Survey using an automated deterministic, smoothed-minima hydrograph separation program.

The U.S. Geological Survey has also compiled a geospatial dataset of the hydrologic landscape regions of the United States (Wolock, 2003b and Wolock, 2004). Hydrologic landscape regions provide a framework for regionalizing streamflow characteristics based on the assumption that watersheds with similar slopes, soils, geology, and climate have the same response to precipitation and groundwater and surface-water interactions. The hydrologic landscape regions of Texas consist of watersheds ranging in size from 0.39 square miles to 3,267 square miles, with an average of 104 square miles, aggregated into 12 of the 20 possible hydrologic landscape regions developed by the U.S. Geological Survey.

We grouped the 599 Texas stream gage locations according to hydrologic landscape region and interpolated the average annual streamflow values and the average annual baseflow indices within each region on a 1-kilometer grid. We multiplied the average annual streamflow for each grid cell by the average annual baseflow to calculate a dataset describing the baseflow volume as a fraction of the average annual streamflow. We then used the ArcGIS zonal statistics tool to assign the average annual baseflow for each watershed polygon. Finally, the hydrologic landscape regions were intersected with the outcrop areas of the major and minor aquifers to create a map of the estimated baseflows from groundwater to surface waters of Texas for each hydrological landscape unit overlying an aquifer (Figure 3-2).

3.3 Summary

The estimated average annual baseflow from each aquifer is listed in Table 3-2 and illustrated graphically in Figure 3-3. In total, the net estimated average flow from the major and minor aquifers of Texas to surface water is about 9.3 million acre-feet per year. This means that on average, slightly less than one-third (about 30 percent) of surface-water flow in Texas is attributable to groundwater discharge from the major and minor aquifers. This represents an average; actual baseflow may vary significantly seasonally, year to year, or in different areas of the state.

The greatest volume of baseflow occurs in East Texas and the Edwards Plateau region, in the aquifer outcrop areas of the Carrizo Wilcox, Edwards (Balcones Fault Zone), Edwards-Trinity (Plateau), Gulf Coast, Queen City, and Sparta aquifers. Major springs in west Texas also locally contribute significant volumes of baseflow to surface water bodies in that region.

The volume of baseflow per unit area of aquifer outcrop follows the general distribution of climatic zones across the state (Figure 3-4). The Edwards (Balcones Fault Zone) Aquifer contributes the most baseflow per unit area of outcrop, followed by the East and Central Texas aquifers. West Texas aquifers produce smaller volumes of baseflow per unit area. The estimated percentage of average annual streamflow in each Texas river basin that is due to baseflow from groundwater is shown in Table 3-3. A larger percentage of streamflow due to baseflow is reflected in river basins that include outcrop areas of aquifers that contribute a significant amount of baseflow.

It should be noted that the baseflow indices represent average annual values estimated from period-of-record streamflow observations prior to any surface water impoundments. The period-of-record dataset may not represent current or future conditions and does not address the inherent seasonal variability of aquifer discharge and recharge processes.

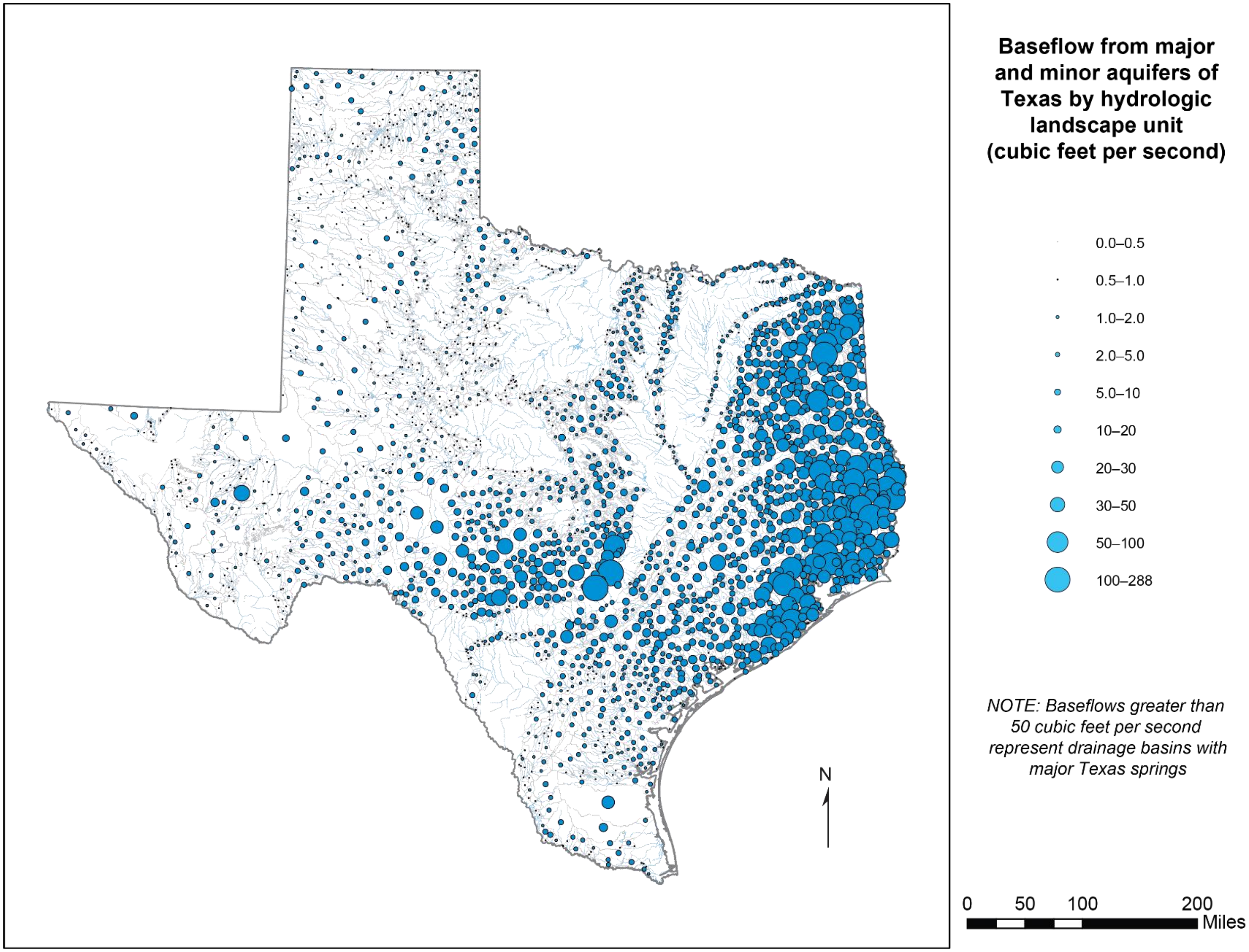


Figure 3-2. **Baseflow from major and minor aquifers of Texas by hydrologic landscape unit (in cubic feet per second).**

Table 3-2. Streamflow and baseflow estimates for the major and minor aquifers.

Aquifer	Average annual streamflow over aquifer outcrop (acre-feet per year) [1]	Average baseflow over aquifer outcrop (acre-feet per year)[1]	Percentage of streamflow due to groundwater discharge from aquifers
Blaine	132,000	29,900	23
Blossom	105,000	14,600	14
Bone Spring-Victorio Peak	15,300	6,710	44
Brazos River Alluvium	293,000	69,500	24
Capitan Reef Complex	3,450	667	19
Carrizo-Wilcox	4,380,000	1,100,000	25
Dockum	96,700	13,200	14
Edwards (Balcones Fault Zone)	678,000	487,000	72
Edwards-Trinity (High Plains)	592	100	17
Edwards-Trinity (Plateau)	1,480,000	818,000	55
Ellenburger-San Saba	87,700	29,000	33
Gulf Coast	13,900,000	3,810,000	27
Hickory	20,600	7,900	38
Hueco-Mesilla Bolsons	15,400	4,830	31
Igneous	114,000	18,300	16
Lipan	28,900	8,280	29
Marathon	10,500	2,060	20
Marble Falls	14,800	4,380	30
Nacatoch	486,000	67,700	14
Ogallala	473,000	121,000	26
Pecos Valley	67,700	47,300	70
Queen City	3,360,000	1,050,000	31
Rita Blanca[2]	-	-	-
Rustler	6,350	1,460	23
Seymour	136,000	28,500	21
Sparta	565,000	189,000	33
Trinity	1,630,000	552,000	34
West Texas Bolsons	13,500	4,000	30
Woodbine	518,000	73,700	14
Yegua-Jackson	2,370,000	714,000	30
Total (acre-feet per year)	**31,001,492**	**9,273,087**	**-**

[1] Estimated flows for each aquifer rounded to three significant figures. Differences between the totals presented in this table and Table 3-3 are a result of rounding.

[2] The Rita Blanca Aquifer does not have an outcrop area; therefore, there is no contribution of groundwater to surface-water flow.

Table 3-3. Streamflow and baseflow estimates for the Texas river basins.

River basin	Average annual streamflow (acre-feet per year) [1]	Average baseflow over aquifer outcrop (acre-feet per year)[1]	Percentage of streamflow due to groundwater discharge from aquifers
Brazos	2,660,000	613,000	23
Brazos-Colorado	835,000	222,000	27
Canadian	204,000	50,700	25
Colorado	1,650,000	645,000	39
Colorado-Lavaca	458,000	60,700	13
Cypress	1,500,000	489,000	33
Guadalupe	1,030,000	732,000	71
Lavaca	715,000	128,000	18
Lavaca-Guadalupe	445,000	61,100	14
Neches	4,810,000	1,810,000	38
Neches-Trinity	1,020,000	231,000	23
Nueces	1,040,000	367,000	35
Nueces-Rio Grande	518,000	80,500	16
Red	658,000	152,000	23
Rio Grande	819,000	407,000	50
Sabine	3,490,000	997,000	29
San Antonio	560,000	210,000	38
San Antonio-Nueces	398,000	64,900	16
San Jacinto	2,210,000	500,000	23
San Jacinto-Brazos	1,220,000	342,000	28
Sulphur	872,000	179,000	21
Trinity	3,290,000	877,000	27
Trinity-San Jacinto	153,000	34,000	22
Total (acre-feet per year)	**30,555,000**	**9,252,900**	**-**

[1] Estimated flows for each aquifer rounded to three significant figures. Differences between the totals presented in this table and Table 3-2 are a result of rounding.

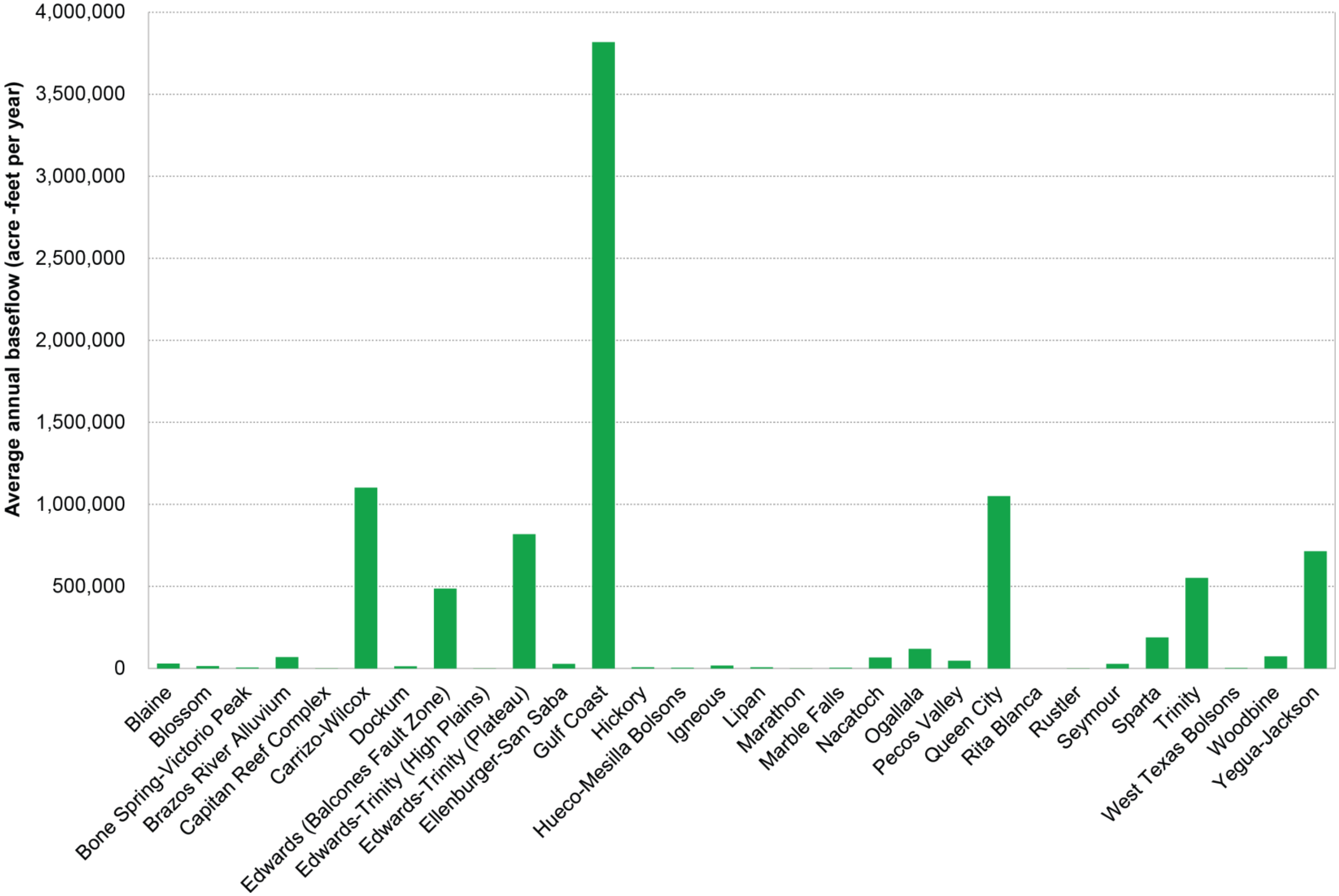


Figure 3-3. Estimated average annual baseflow contributions to surface water (acre-feet per year).

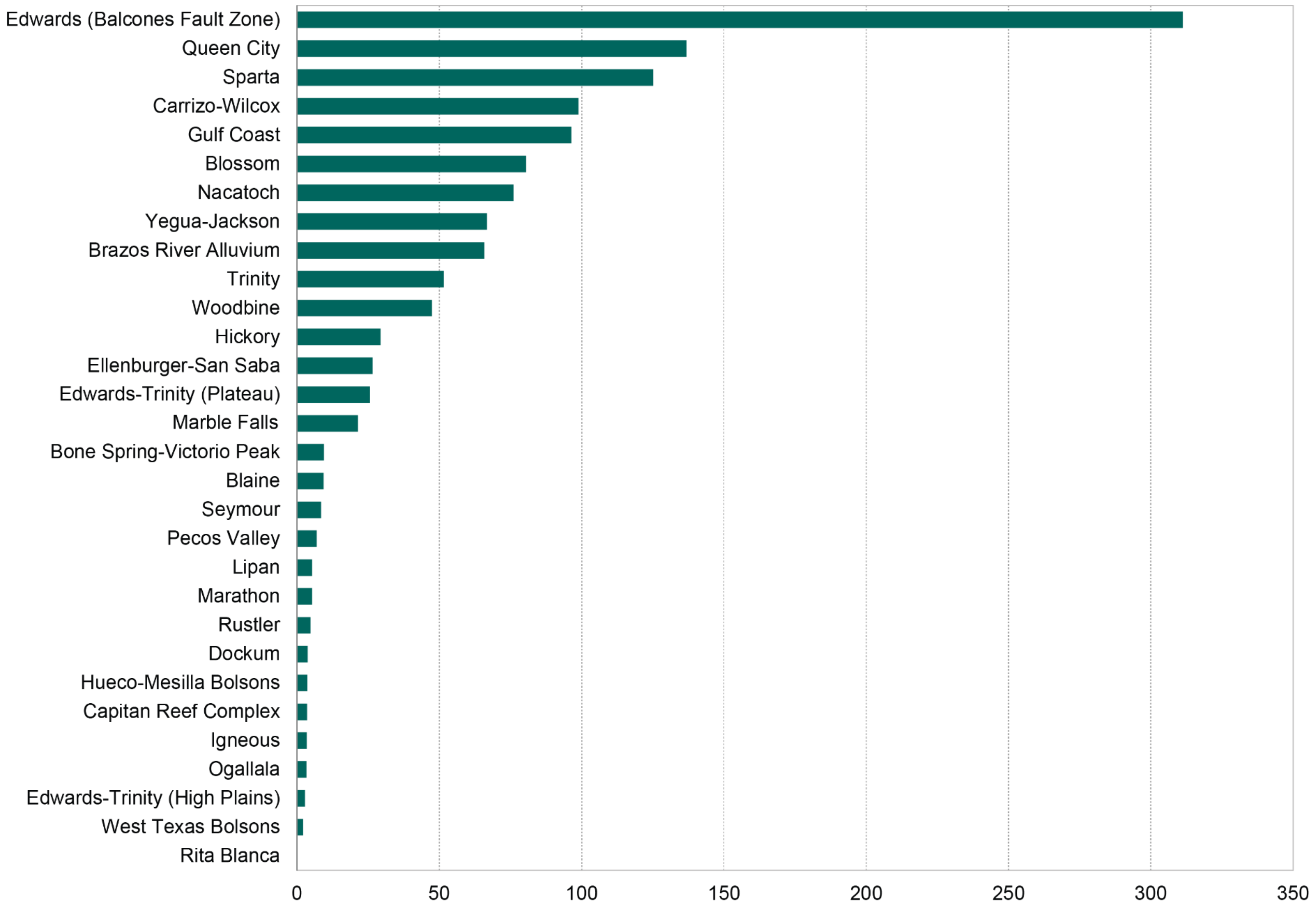


Figure 3-4. **Ratio of baseflow to aquifer outcrop area.**

4 Tributary and Non-Tributary Groundwater

Key points:

- We used baseflow data for the major and minor aquifers (Chapter 3) to categorize the tributary nature of Texas aquifers. Nearly all Texas aquifers discharge groundwater to streams and rivers that flow over their outcrop areas. We consider these aquifers to be tributary for the purposes of this study. However, each of the aquifers has local areas that may differ from the regional, aggregate designation.
- Better methods and data for quantifying groundwater and surface-water interactions are needed. The baseflow analysis used for this report relies on historical streamflow and spring discharge data that may not completely or accurately represent present or future conditions given the widespread drawdown of groundwater levels observed statewide.

The question of defining or designating tributary or non-tributary aquifers with specific, quantitative criteria has not been resolved on a nationwide basis, although certain states have adopted specific definitions that are tailored to their water management regulatory programs. For example, Colorado, a state that owns and regulates all water resources within its boundaries, has applied the concept of tributary aquifers to the adjudication or allocation of groundwater resources (Colorado Department of Natural Resources, 2016). The general definition that tributary groundwater is "groundwater that discharges into surface water" is silent in terms of the criteria to define the definitional boundaries between tributary and non-tributary aquifers. Colorado defines nontributary groundwater to be groundwater pumped at a well that will not deplete the flow of a stream at an annual rate greater than one-tenth of 1 percent of the annual rate of withdrawal. Such a specific, locally-scoped definition is problematic to use when evaluating the regional aquifer systems in Texas. Therefore, strictly speaking, groundwater in nearly every aquifer in Texas has some degree of movement into or out of surface water and could be considered as tributary.

We have evaluated the available surface-water and groundwater data to identify aquifers that could be considered tributary. These available data—generated by multiple federal, state, and academic organizations—are inherently uneven in terms of areal coverage, time and duration of measurements, and quality. Moreover, this situation is likely to remain the same for the foreseeable future. Further evaluation of data and inclusion of additional information as it becomes available may lead to an appropriate modification of our definition. As a basis for identifying tributary aquifers, we charted the estimated percentage of surface-water flow over the aquifer outcrop area that is attributable to groundwater discharge (Figure 4-1 and Table 4-1).

We chose to look at percentages, rather than absolute numbers, to normalize the effects of the different climate regions in the state. Based on the available data, all Texas aquifers (with the possible exception of the Rita Blanca Aquifer, which has no surface outcrop in the state) could be considered tributary aquifers since some groundwater from each aquifer does discharge to surface water. However, that approach obscures the fact that there are clear distinctions between Texas aquifers in the degree and significance of groundwater and surface-water interactions.

The statewide range of percentage of streamflow attributable to baseflow from aquifers shown in Figure 4-1 reveals a wide variation in the degree of regional groundwater-surface water interactions. While these percentages apply to regional aquifers—some of which cover thousands of square miles—it is more likely than not that within these aquifers there exists significant variation with respect to the degree of groundwater contributions to surface water.

This analysis applies specifically to the outcrop or unconfined areas of Texas aquifers. Confined portions of the aquifers are generally more isolated from interaction with surface water and can generally be considered "non-tributary," although springs, such as San Solomon Springs in West Texas, can originate from confined aquifers and may create local tributary aquifer zones. Groundwater discharge from three major aquifers—the Edwards (Balcones Fault Zone), Edwards-Trinity (Plateau), and Pecos Valley aquifers—contributes more than 50 percent of the baseflow of streams flowing across their outcrop zones on an average annual basis. This is supported by the number of current and historical springs that flow from these aquifers. Eighteen major and minor aquifers contribute between 20 and 50 percent of flow to streamflow over their outcrop zones. Eight minor aquifers contribute between 14 and 20 percent of the flow to streams flowing over their outcrop zones. These aquifers include the Blossom, Capitan Reef Complex, Dockum, Edwards-Trinity (High Plains), Igneous, Marathon, Nacatoch, and Woodbine aquifers. One minor aquifer, the Rita Blanca, contributes zero percent to streamflow in Texas and is classified as non-tributary. A map of the tributary and non-tributary aquifers of Texas is provided as Figure 4-2.

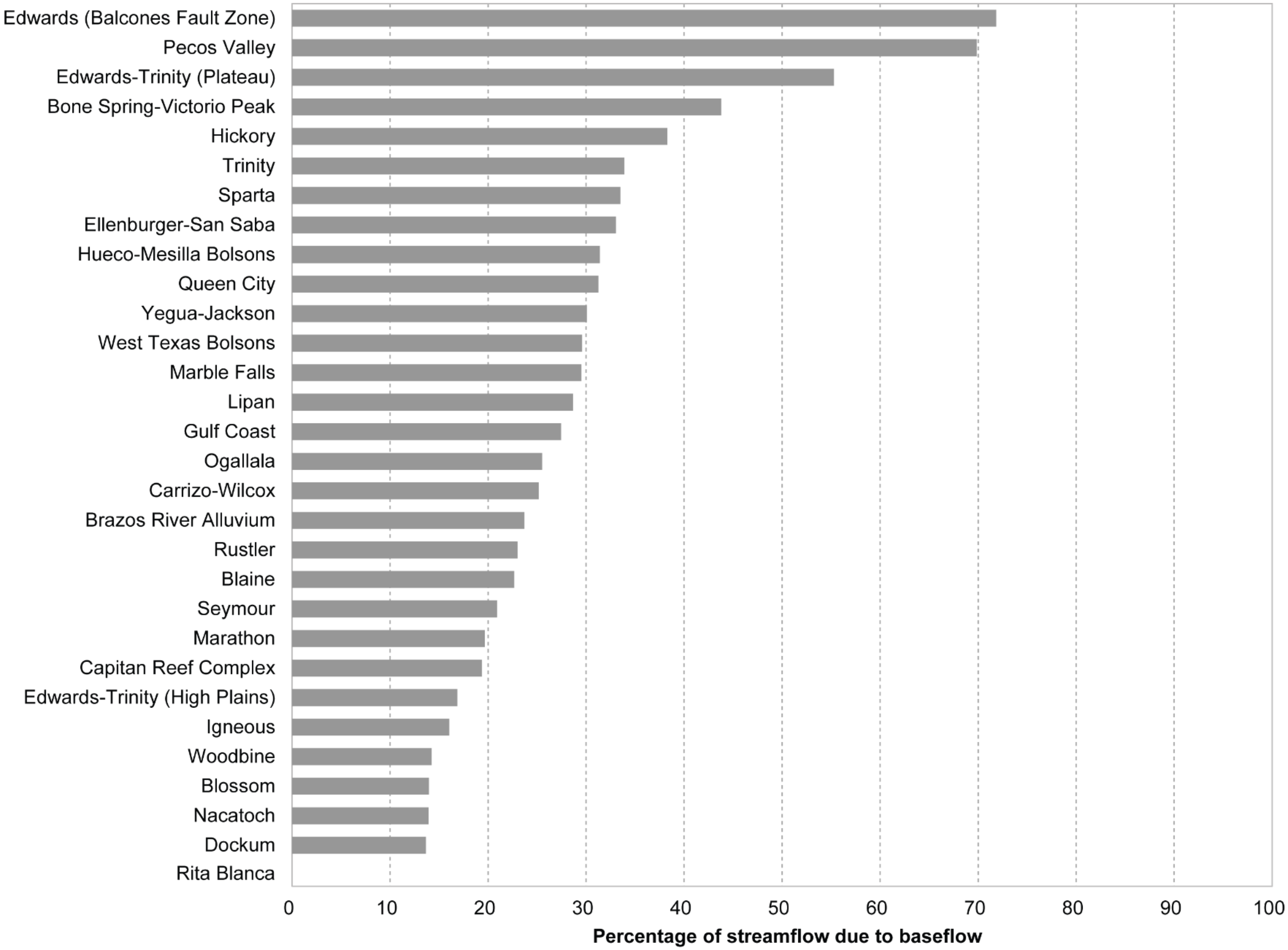


Figure 4-1. Percentage of streamflow due to baseflow from groundwater for major and minor aquifers in Texas.

Table 4-1. Percentage of streamflow in aquifer outcrop area from groundwater.

Aquifer	Percentage of streamflow in aquifer outcrop area from groundwater
Blaine	23
Blossom	14
Bone Spring-Victorio Peak	44
Brazos River Alluvium	24
Capitan Reef Complex	19
Carrizo-Wilcox	25
Dockum	14
Edwards (Balcones Fault Zone)	72
Edwards-Trinity (High Plains)	17
Edwards-Trinity (Plateau)	55
Ellenburger-San Saba	33
Gulf Coast	27
Hickory	38
Hueco-Mesilla Bolsons	31
Igneous	16
Lipan	29
Marathon	20
Marble Falls	30
Nacatoch	14
Ogallala	26
Pecos Valley	70
Queen City	31
Rita Blanca	0
Rustler	23
Seymour	21
Sparta	33
Trinity	34
West Texas Bolsons	30
Woodbine	14
Yegua-Jackson	30

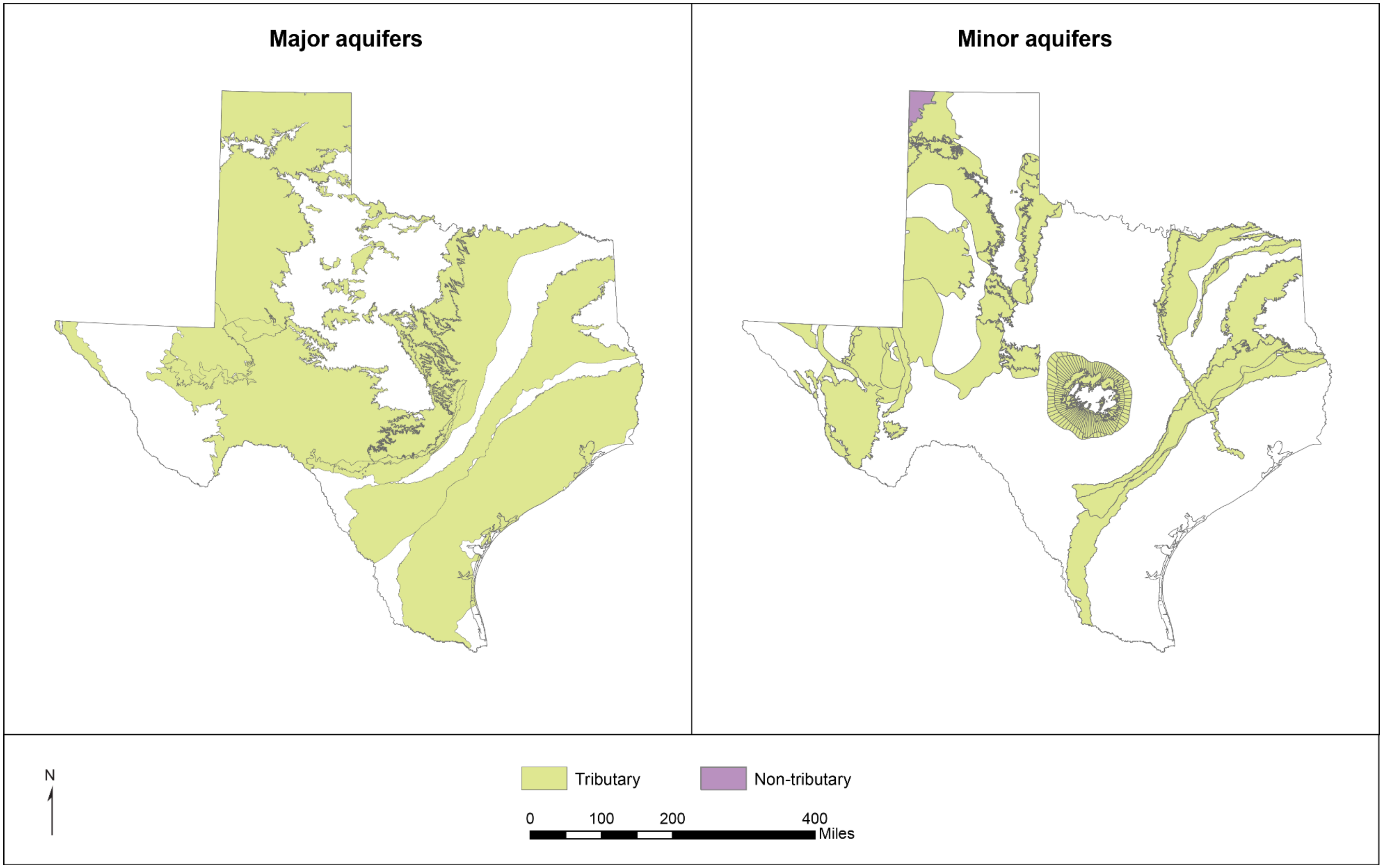


Figure 4-2. **Tributary and non-tributary aquifers of Texas.**

5 Groundwater Flows to Other Aquifers

Key points:

- There are no direct measurements of groundwater flow between aquifers. Estimates of inter-aquifer groundwater flow are best made by simulating flow conditions with groundwater availability models.
- Groundwater flow between the major and minor aquifers in the eastern part of Texas is limited by the thick sequences of shale or clay that separate the aquifer systems and generally restrict vertical groundwater movement between them. Conceptually, it is probable that over time groundwater in deep confined aquifers ultimately discharges regionally into overlying strata.
- Some aquifers in the central and western areas of the state are juxtaposed such that lateral groundwater flow probably occurs between them.
- Some groundwater availability models can be used to estimate flow between aquifers. However, many groundwater availability models have been designed with "no-flow" boundaries, precluding estimates of groundwater flow across those confining boundaries.
- Different model conceptualization would be needed to account for potential flows across those boundaries in response to pumping stresses.
- Groundwater flow between aquifers occurs primarily in the Hill Country, especially along the southern and eastern edge of the Edwards Plateau, and in the Pecos Valley.
- In the High Plains, some groundwater flow occurs from the Ogallala Aquifer to the Dockum Aquifer.
- The groundwater availability models used for the current estimates were not generally designed or calibrated with this application in mind, and different models produced widely varying results in areas of overlap.

5.1 Background

No direct measurements of inter-aquifer groundwater flow are available. Many aquifers—particularly in the eastern half of Texas—are bounded by thick sequences of shale or clay that isolate aquifers from each other and limit inter-aquifer groundwater flow. Therefore, inter-aquifer flow needs to be evaluated indirectly using groundwater flow models or by other analytical means. There are some situations in which groundwater level data in different aquifers can be compared to evaluate hydraulic gradients between aquifers and develop an indirect estimate of possible groundwater flow. In other cases, aquifers may contact other aquifers along lateral boundaries—such as along geologic fault zones—so that inter-aquifer flow may occur across those boundaries. Inter-aquifer groundwater flow can occur wherever a route for flow exists through direct physical contact of aquifers combined with a hydraulic gradient between the aquifers. To a lesser degree inter-aquifer groundwater flow may be possible over the long term between aquifers that are separated by low permeability shale or clay layers. For example, Huang and others (2012) note that in the Carrizo-Wilcox Aquifer groundwater moving through the deep confined portions probably discharges regionally to overlying strata. Typical groundwater flow patterns in the state's aquifers involve recharge to the aquifer at the surface in the outcrop zone and discharge to streams as baseflow or through pumping or evapotranspiration. Some groundwater also moves into deeper confined portions of aquifers or to other aquifers as inter-aquifer flow.

Prior to groundwater pumping in Texas, which altered hydraulic gradients in most aquifers, the recharge and discharge—including flows between aquifers—were balanced so there was little or no change in the amount of groundwater stored in aquifers. Groundwater pumping alters prevailing hydraulic gradients and, in some cases, reverses the direction of the gradient. This has been documented by Huang and others (2012) in areas of the Carrizo-Wilcox Aquifer where pumping has reversed the gradient from upward to downward relative to the overlying Queen City Aquifer. However, there is no documentation that groundwater flow directions have been correspondingly altered since long periods of time—decades or centuries—may be necessary to change flow directions when thick sequences of low permeability materials separate the aquifers.

5.2 Estimates of inter-aquifer groundwater flow

For the purposes of this study, we have considered steady-state (no pumping) groundwater conditions as presented in the various groundwater availability models. Groundwater availability models represent the best available compilation of hydrogeological data and processes with which to make such an estimate, but in most cases the models were not specifically designed or calibrated to estimate inter-aquifer flow. Groundwater availability models were developed for specific aquifers and use assumptions and conditions in their construction that may be different from groundwater availability models for other aquifers. Therefore, caution is necessary in reviewing and evaluating inter-aquifer groundwater flow estimates and particularly in comparing values for the same aquifer relationships estimated using different groundwater flow models.

We estimated inter-aquifer groundwater flow considering the following:

- flow in major and minor aquifers that are in direct contact with each other;
- flow within aquifers (for example, flow between the Chicot and Jasper aquifers within the Gulf Coast Aquifer System) was not considered;

- steady-state (pre-development) conditions were assumed; and
- groundwater availability models were used to develop groundwater flow estimates.

Vertical flow between aquifers

Aquifers bounded by low-permeability geological units have little or no interaction with neighboring aquifers. Figure 5-1 partially illustrates this for the Hill Country portion of the Trinity Aquifer, which has a low permeability confining layer that limits groundwater flow at its lower boundary. Therefore, the confining layer below the aquifer is coded in the groundwater availability model as a no-flow boundary even though some flow could occur under certain pumping scenarios. This approach is applicable to a number of Texas aquifers, is well-grounded in available data and science, and is based on a consensus of groundwater hydrologists and geologists across Texas who developed or peer-reviewed the conceptual models that were used to construct the numerical groundwater flow models.

Lateral flow between aquifers

Lateral groundwater flow can occur between aquifers where they overlap or are in contact with each other. The magnitude and direction of flow depends on the difference in hydraulic head between groundwater in the two aquifers as well as the hydraulic properties of the aquifer. In some cases, there is sufficient water level data in the contact area and these inter-aquifer flows are explicitly addressed in model development and calibration. In other cases, there are relatively little data for model calibration and/or inter-aquifer flows are small compared to flows within the aquifers and as a result the model values are poorly constrained. The Trinity Aquifer conceptual model also shows how lateral groundwater flow can occur between aquifers that are juxtaposed. Figure 5-1 also illustrates the conditions on the eastern boundary of the Trinity Aquifer, which is bounded by the Balcones Fault Zone and the Edwards (Balcones Fault Zone) Aquifer. In this case, groundwater flows eastward according to the prevailing hydraulic gradient into the Edwards (Balcones Fault Zone) Aquifer.

Table 5-1 summarizes estimates of inter-aquifer flows for the major and minor aquifers based on simulations of groundwater flow using groundwater availability models. In some cases, flows are listed for both directions between two aquifers; because of the large extent of some aquifers, flows may occur in one direction in one area of the aquifer and in the opposite direction in another area. In several cases, more than one model was used to assess inter-aquifer flows. Models may provide very different estimates that are attributable to a different conceptualization of the aquifer, variable boundary conditions, and different model codes. In these cases, the average value of the flow estimates is shown. The wide range of values—ranging from less than 10 to well over 50,000 acre-feet per year—reflect the area over which groundwater flux was estimated, and the variability of groundwater flows through complex aquifers.

Table 5-2 presents a detailed tabulation of simulated inter-aquifer groundwater flows on an aquifer and county basis. Several of the inter-aquifer flow values were estimated using different groundwater flow models in areas where several aquifers overlapped and had dedicated models with unique attributes and conceptual features. These situations resulted in different flow results for aquifers in the same region, illustrating the very approximate nature of developing inter-aquifer flow estimates using groundwater availability models.

The magnitude and location of inter-aquifer groundwater flow is unevenly distributed across Texas (Figure 5-2). The directions of the arrows approximate the lateral groundwater flow direction; however, in some cases actual flow may be primarily vertical. Ten counties have groundwater fluxes between multiple aquifers; for these counties only the largest flux is shown for clarity.

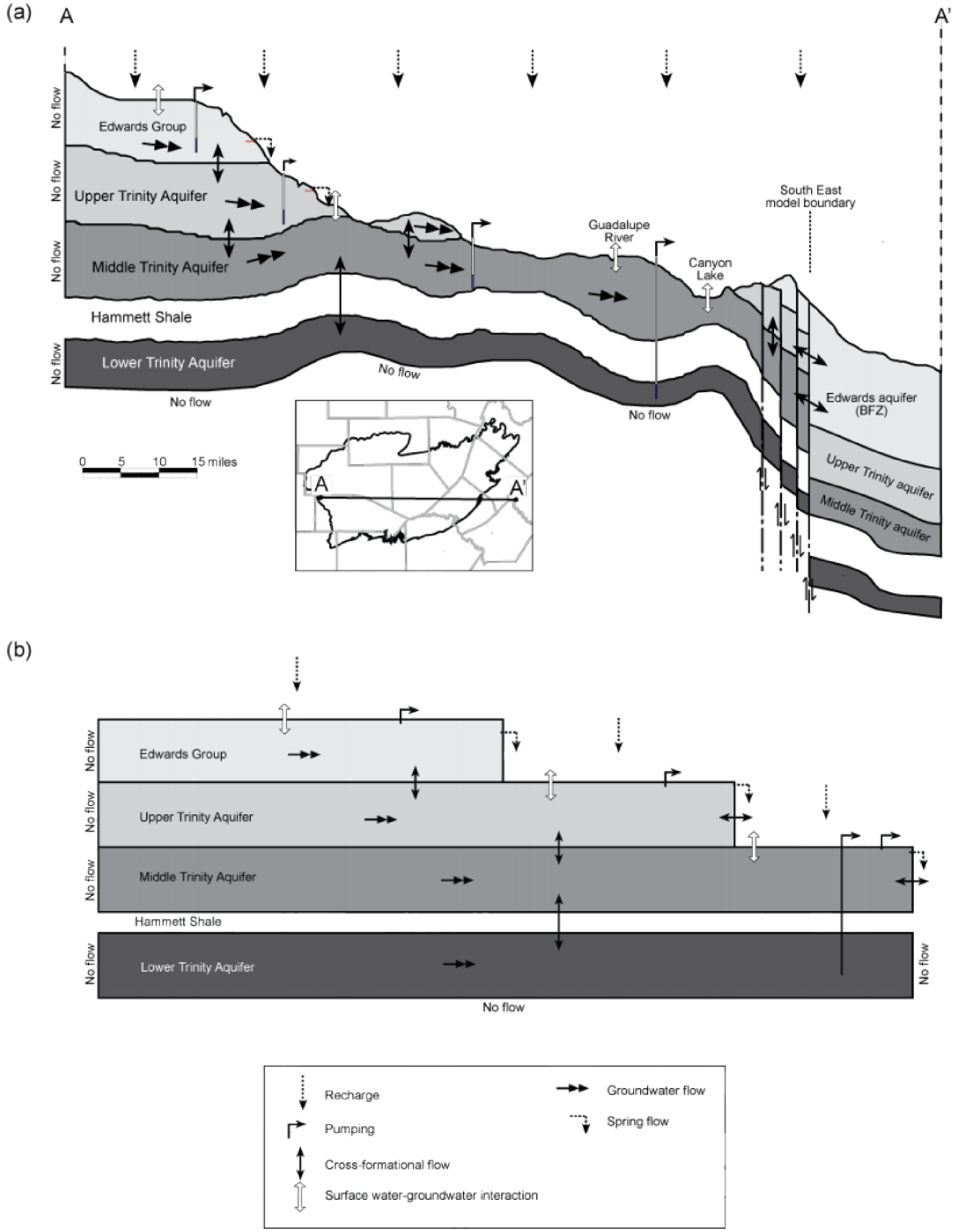


Figure 5-1. **Conceptual model diagram of the Hill Country portion of the Trinity Aquifer system showing a (a) schematic cross-section and (b) conceptual model with flows between layers (Jones and others, 2009).**

Table 5-1. Modeled estimates of inter-aquifer flows between the major and minor aquifers of Texas.

Flow from	Flow to	Total flow (acre-feet per year)	Remarks
Blaine Aquifer	Seymour Aquifer	34,072	TWDB staff model analysis
Seymour Aquifer	Blaine Aquifer	7,162	TWDB staff model analysis
Carrizo-Wilcox Aquifer	Brazos River Alluvium Aquifer	2,361	TWDB staff model analysis
Dockum Aquifer	Edwards-Trinity (Plateau) Aquifer	37,509	TWDB staff model analysis
Edwards-Trinity (Plateau) Aquifer	Dockum Aquifer	2,948	TWDB staff model analysis
Dockum Aquifer	Ogallala Aquifer	2,241	TWDB staff model analysis
Ogallala Aquifer	Dockum Aquifer	27,497	TWDB staff model analysis
Dockum Aquifer	Rita Blanca Aquifer	115	TWDB staff model analysis
Rita Blanca Aquifer	Dockum Aquifer	83	TWDB staff model analysis
Rustler Aquifer	Dockum Aquifer	1	TWDB staff model analysis
Edwards (Balcones Fault Zone) Aquifer	Trinity Aquifer	9,381	TWDB staff model analysis – averaged value
Trinity Aquifer	Edwards (Balcones Fault Zone) Aquifer	61,463	TWDB staff model analysis – includes San Antonio, Barton Springs, and Northern segments
Edwards-Trinity (Plateau) Aquifer & Other Formations	Lipan Aquifer	7,507	TWDB staff model analysis
Lipan Aquifer	Edwards-Trinity (Plateau) Aquifer & otherformations	7,506	TWDB staff model analysis
Edwards-Trinity (High Plains) Aquifer	Ogallala Aquifer	5,544	TWDB staff model analysis
Ogallala Aquifer	Edwards-Trinity (High Plains) Aquifer	13,812	TWDB staff model analysis
Edwards-Trinity (Plateau) Aquifer	Edwards (Balcones Fault Zone) Aquifer	25,626	TWDB staff model analysis
Edwards-Trinity (Plateau) Aquifer	Ellenburger-San Saba Aquifer	929	TWDB staff model analysis

Table 5-1 (continued). Modeled estimates of inter-aquifer flows between the major and minor aquifers of Texas.

Flow from	Flow to	Total flow (acre-feet per year)	Remarks
Edwards-Trinity (Plateau) Aquifer	Hickory Aquifer	43	TWDB staff model analysis
Edwards-Trinity (Plateau) Aquifer	Marble Falls Aquifer	7	TWDB staff model analysis
Edwards-Trinity (Plateau) Aquifer	Ogallala Aquifer	7,341	TWDB staff model analysis
Ogallala Aquifer	Edwards-Trinity (Plateau) Aquifer	3,014	TWDB staff model analysis
Edwards-Trinity (Plateau) Aquifer	Pecos Valley Aquifer	45,966	TWDB staff model analysis
Pecos Valley Aquifer	Edwards-Trinity (Plateau) Aquifer	647	TWDB staff model analysis
Ogallala Aquifer	Pecos Valley Aquifer	220	TWDB staff model analysis
Pecos Valley Aquifer	Ogallala Aquifer	0	TWDB staff model analysis
Edwards-Trinity (Plateau) Aquifer	Trinity Aquifer	21,848	TWDB staff model analysis
Trinity Aquifer	Edwards-Trinity (Plateau) Aquifer	20,546	TWDB staff model analysis
Ellenburger-San Saba Aquifer	Hickory Aquifer	9,305	TWDB staff model analysis
Hickory Aquifer	Ellenburger-San Saba Aquifer	21,654	TWDB staff model analysis
Ellenburger-San Saba Aquifer	Marble Falls Aquifer	2,368	TWDB staff model analysis
Marble Falls Aquifer	Ellenburger-San Saba Aquifer	3,647	TWDB staff model analysis
Hickory Aquifer	Trinity Aquifer	64	TWDB staff model analysis
Ogallala Aquifer	Rita Blanca Aquifer	1,670	TWDB staff model analysis
Trinity Aquifer	Ellenburger-San Saba Aquifer	1,285	TWDB staff model analysis
Trinity Aquifer	Marble Falls Aquifer	144	TWDB staff model analysis

Note: Estimates are based on steady-state (no pumping) simulations of groundwater flow. Groundwater pumping in these aquifers would alter the dynamic equilibrium and result in different estimates of inter-aquifer flow rates.

Regional summaries

West and Central Texas

Aquifers in West and South Texas, particularly the Edwards Trinity (Plateau) and Pecos Valley aquifers, are flat-lying and directly contact each other without confining low permeability shale or clay. This geometry presents an opportunity for groundwater flow between aquifers. Other aquifers, such as the West Texas Bolsons or Igneous aquifers, are isolated or individual closed basins and offer little opportunity for inter-aquifer groundwater flow. Groundwater flows between aquifers are complex and poorly understood in some areas. For example, some major springs in Pecos County that discharge through the Edwards Trinity (Plateau) Aquifer may represent groundwater that originates in or traverses through other aquifers. Lateral movement of groundwater from the Edwards Trinity (Plateau) Aquifer and Trinity Aquifer to the Edwards (Balcones Fault Zone) Aquifer has been estimated in a number of studies (for example, Clark and Journey [2006] and Wong and others [2014]).

Regions of inter-aquifer flow include the following:

- Pecos and Reeves counties, where groundwater flows from the Edwards-Trinity (Plateau) Aquifer into the Pecos Valley Aquifer
- The Hill Country, where groundwater in the Edwards-Trinity (Plateau) Aquifer flows into the Edwards (Balcones Fault Zone), Trinity, and minor aquifers around the Llano Uplift
- Bell, Travis, and Williamson counties, where the Edwards (Balcones Fault Zone) Aquifer groundwater flows into the Trinity aquifer
- South central Texas where Trinity groundwater flows into the Edwards-Trinity (Plateau), Edwards (Balcones Fault Zone), and Llano Uplift aquifers

Panhandle and Northwest Texas

Aquifers in the Panhandle and northwest Texas, particularly the Ogallala, Edwards-Trinity (High Plains), and Dockum aquifers are flat lying and locally contact each other without intervening low permeability shale or clay. This geometry presents an opportunity for direct interaction between these aquifers.

Areas of inter-aquifer flow include the following:

- The High Plains, where Ogallala Aquifer groundwater flows into the Dockum, Edwards-Trinity (High Plains), and Pecos Valley aquifers
- The area of Collingsworth, Hall, Kent, and Stonewall counties, where Seymour Aquifer groundwater flows into the Blaine Aquifer

Gulf Coast, North, and East Texas

Major and minor aquifers in this region dip toward the Gulf of Mexico and are separated from each other by thick sequences of clay and shale. Direct groundwater flow between these aquifers is limited, although it is possible that at depth there may be inter-aquifer movement of groundwater under pressure, and along growth fault zones.

Areas of inter-aquifer flow include

- Milam and Robertson counties, where groundwater from the Carrizo-Wilcox Aquifer flows into the Brazos River Alluvium Aquifer.

5.3 Estimates of inter-aquifer groundwater flow required for groundwater management plans

For groundwater conservation districts, the TWDB estimates the "annual flow into and out of the district within each aquifer and between aquifers in the district, if a groundwater availability model is available" in compliance with Texas Water Code §36.1071(e). These estimates are provided to groundwater conservation districts for inclusion in their groundwater management plan. Because these estimates are prepared for specific districts, the groundwater flow values for these plans are limited to the area within the boundaries of each district. On the regional scale called for by this study, the summing of values for multiple districts for a major or minor aquifer would be incomplete because the administrative boundaries of districts do not coincide with aquifer boundaries.

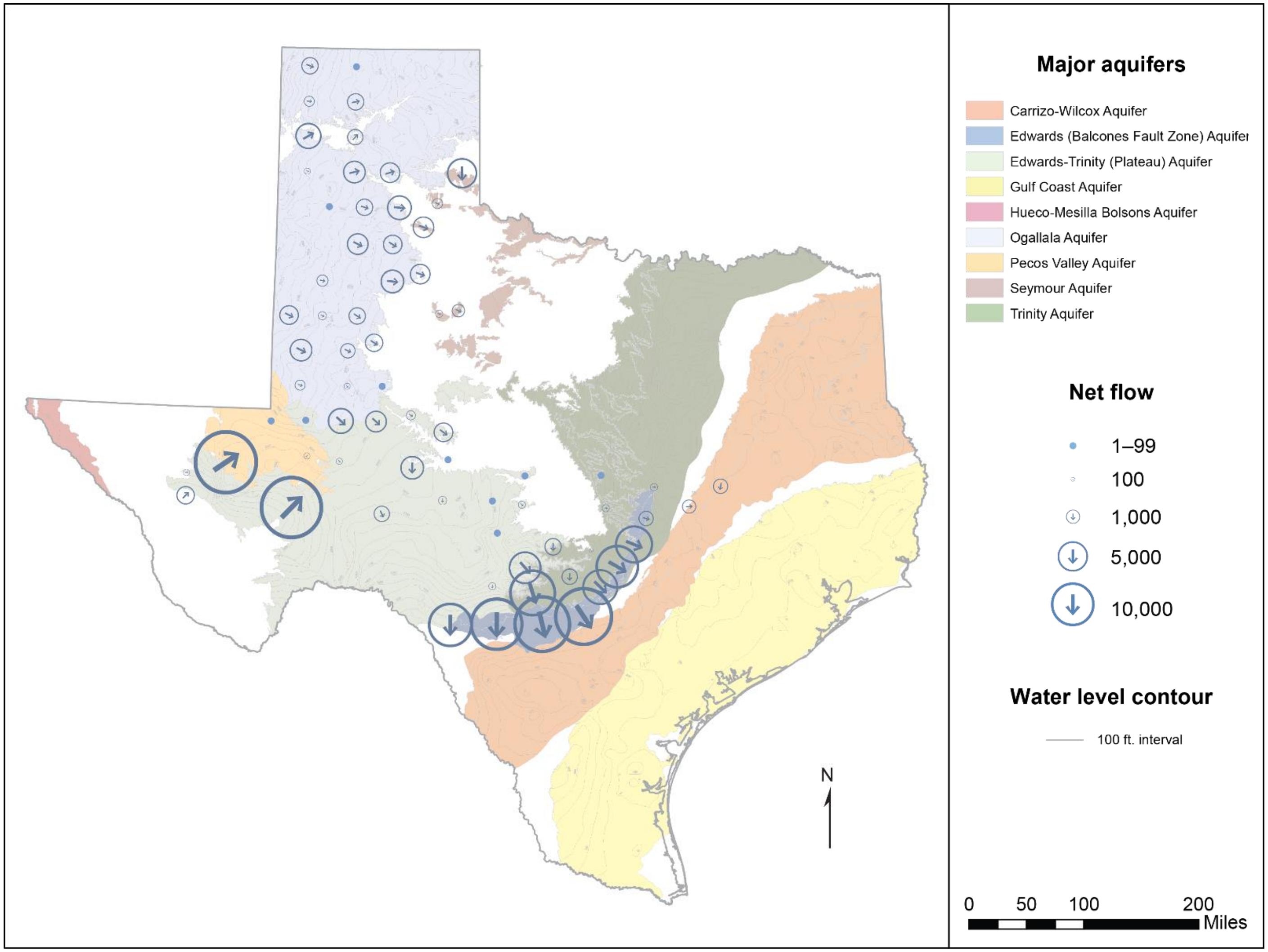


Figure 5-2. **Estimated groundwater fluxes from major aquifers of Texas to other aquifers, by county. Arrow size is proportional to average annual flow, in acre feet, as determined by groundwater availability models; arrow direction approximates groundwater flow, based on water level contours.**

Table 5-2. Detailed modeled estimates of inter-aquifer flows between major and minor aquifers in Texas counties.

County	From aquifer	To aquifer	Average annual net flow (acre feet per year)	Groundwater availability model (GAM)	Comments
Andrews	Dockum	Ogallala	16	High Plains Aquifer System GAM v1.01	
Andrews	Dockum	Edwards-Trinity (Plateau)	11	High Plains Aquifer System GAM v1.01	
Andrews	Edwards-Trinity (Plateau)	Ogallala	1,085	Edwards Trinity (Plateau) and Pecos Valley GAM v. 1.01	Different models show flow reversal
Andrews	Ogallala	Pecos Valley	182	High Plains Aquifer System GAM v1.01	
Andrews	Ogallala	Edwards-Trinity (Plateau)	212	High Plains Aquifer System GAM v1.01	Different models show flow reversal
Andrews	Pecos Valley	Ogallala	0	Edwards Trinity (Plateau) and Pecos Valley GAM v. 1.01	
Armstrong	Ogallala	Dockum	2,174	High Plains Aquifer System GAM v1.01	
Baily	Ogallala	Edwards-Trinity (High Plains)	396	High Plains Aquifer System GAM v1.01	
Bandera	Edwards-Trinity (Plateau)	Trinity	12,911	Edwards Trinity (Plateau) and Pecos Valley GAM v. 1.01	
Bandera	Trinity	Edwards (Balcones Fault Zone)	2,621	Edwards Trinity (Plateau) and Pecos Valley GAM v. 1.01	
Bandera	Trinity	Edwards-Trinity (Plateau)	1,430	Draft Llano Uplift GAM	
Bell	Edwards (Balcones Fault Zone)	Trinity	352	Northern Trinity Woodbine GAM v2.01	

Table 5-2 (continued). Detailed modeled estimates of inter-aquifer flows between major and minor aquifers in Texas counties.

County	From aquifer	To aquifer	Average annual net flow (acre feet per year)	Groundwater availability model (GAM)	Comments
Bexar	Trinity	Edwards (Balcones Fault Zone)	5,831	Edwards (Balcones Fault Zone) San Antonio segment	Different models show different average flux
Bexar	Trinity	Edwards (Balcones Fault Zone)	30,810	Edwards Trinity (Plateau) and Pecos Valley GAM v. 1.01	Different models show different average flux
Blanco	Ellenburger-San Saba	Marble Falls	474	Draft Llano Uplift GAM	
Blanco	Hickory	Trinity	63	Draft Llano Uplift GAM	
Blanco	Hickory	Ellenburger-San Saba	4,124	Draft Llano Uplift GAM	
Blanco	Trinity	Edwards-Trinity (Plateau)	164	Edwards Trinity (Plateau) and Pecos Valley GAM v. 1.01	Different models show different average flux
Blanco	Trinity	Edwards-Trinity (Plateau)	38	Draft Llano Uplift GAM	Different models show different average flux
Blanco	Trinity	Marble Falls	99	Draft Llano Uplift GAM	
Blanco	Trinity	Ellenburger-San Saba	953	Draft Llano Uplift GAM	
Borden	Ogallala	Edwards-Trinity (High Plains)	1,918	High Plains Aquifer System GAM v1.01	

Table 5-2 (continued). Detailed modeled estimates of inter-aquifer flows between major and minor aquifers in Texas counties.

County	From aquifer	To aquifer	Average annual net flow (acre feet per year)	Groundwater availability model (GAM)	Comments
Briscoe	Ogallala	Dockum	3,395	High Plains Aquifer System GAM v1.01	
Burnet	Ellenburger-San Saba	Marble Falls	1,070	Draft Llano Uplift GAM	
Burnet	Hickory	Trinity	1	Draft Llano Uplift GAM	
Burnet	Hickory	Ellenburger-San Saba	7,659	Draft Llano Uplift GAM	
Burnet	Trinity	Marble Falls	8	Draft Llano Uplift GAM	
Burnet	Trinity	Ellenburger-San Saba	274	Draft Llano Uplift GAM	
Carson	Dockum	Ogallala	112	High Plains Aquifer System GAM v1.01	
Castro	Ogallala	Dockum	25	High Plains Aquifer System GAM v1.01	
Childress	Blaine	Seymour	2,9443	Seymour Aquifer GAM v_1.01	
Cochran	Edwards-Trinity (High Plains)	Ogallala	110	High Plains Aquifer System GAM v1.01	
Coke	Edwards-Trinity (Plateau)	Dockum	63	High Plains Aquifer System GAM v1.01	
Coke	Edwards Trinity Plateau & Other Formations	Lipan	1,961	Lipan GAM v_1.01	
Collingsworth	Seymour	Blaine	4,947	Seymour Aquifer GAM v_1.01	
Comal	Trinity	Edwards (Balcones Fault Zone)	4,395	Edwards (Balcones Fault Zone) San Antonio segment GAM	Different models show different average flux

Table 5-2 (continued). Detailed modeled estimates of inter-aquifer flows between major and minor aquifers in Texas counties.

County	From aquifer	To aquifer	Average annual net flow (acre feet per year)	Groundwater availability model (GAM)	Comments
Comal	Trinity	Edwards (Balcones Fault Zone)	9,680	Edwards Trinity (Plateau) and Pecos Valley GAM v. 1.01	Different models show different average flux
Concho	Lipan	Edwards-Trinity (Plateau) & Other Formations	2,666	Lipan GAM v_1.01	
Crane	Edwards-Trinity (Plateau)	Dockum	108	High Plains Aquifer System GAM v1.01	
Crane	Pecos Valley	Edwards-Trinity (Plateau)	194	Edwards Trinity (Plateau) and Pecos Valley GAM v. 1.01	
Crockett	Dockum	Edwards-Trinity (Plateau)	511	High Plains Aquifer System GAM v1.01	
Crockett	Edwards-Trinity (Plateau)	Pecos Valley	1,385	Edwards Trinity (Plateau) and Pecos Valley GAM v. 1.01	
Crosby	Ogallala	Dockum	3,001	High Plains Aquifer System GAM v1.01	
Culberson	Pecos Valley	Edwards-Trinity (Plateau)	224	Edwards Trinity (Plateau) and Pecos Valley GAM v. 1.01	
Dallam	Dockum	Ogallala	501	High Plains Aquifer System GAM v1.01	
Dallam	Dockum	Rita Blanca	115	High Plains Aquifer System GAM v1.01	
Dallam	Ogallala	Rita Blanca	1,661	High Plains Aquifer System GAM v1.01	
Dawson	Ogallala	Edwards-Trinity (High Plains)	1,200	High Plains Aquifer System GAM v1.01	

Table 5-2 (continued). Detailed modeled estimates of inter-aquifer flows between major and minor aquifers in Texas counties.

County	From aquifer	To aquifer	Average annual net flow (acre feet per year)	Groundwater availability model (GAM)	Comments
Deaf Smith	Ogallala	Dockum	196	High Plains Aquifer System GAM v1.01	
Dickens	Ogallala	Dockum	2,300	High Plains Aquifer System GAM v1.01	
Ector	Edwards-Trinity (Plateau)	Ogallala	4,162	Edwards Trinity (Plateau) and Pecos Valley GAM v. 1.01	Different models show different average flux
Ector	Edwards-Trinity (Plateau)	Ogallala	6	High Plains Aquifer System GAM v1.01	Different models show different average flux
Ector	Edwards-Trinity (Plateau)	Dockum	769	High Plains Aquifer System GAM v1.01	
Ector	Ogallala	Dockum	16	High Plains Aquifer System GAM v1.01	
Ector	Pecos Valley	Edwards-Trinity (Plateau)	0	Edwards Trinity (Plateau) and Pecos Valley GAM v. 1.01	
Fisher	Blaine	Seymour	2,226	Seymour Aquifer GAM v_1.01	
Floyd	Edwards-Trinity (High Plains)	Ogallala	217	High Plains Aquifer System GAM v1.01	
Floyd	Edwards-Trinity (High Plains)	Dockum	1,009	High Plains Aquifer System GAM v1.01	
Floyd	Ogallala	Dockum	2,142	High Plains Aquifer System GAM v1.01	

Table 5-2 (continued). Detailed modeled estimates of inter-aquifer flows between major and minor aquifers in Texas counties.

County	From aquifer	To aquifer	Average annual net flow (acre feet per year)	Groundwater availability model (GAM)	Comments
Gaines	Dockum	Ogallala	1,111	High Plains Aquifer System GAM v1.01	
Gaines	Edwards-Trinity (High Plains)	Dockum	95	High Plains Aquifer System GAM v1.01	
Gaines	Ogallala	Edwards-Trinity (High Plains)	2,786	High Plains Aquifer System GAM v1.01	
Garza	Edwards-Trinity (High Plains)	Ogallala	1,881	High Plains Aquifer System GAM v1.01	
Gillespie	Edwards-Trinity (Plateau)	Trinity	4,339	Draft Llano Uplift GAM	Different models show flow reversal
Gillespie	Edwards-Trinity (Plateau)	Ellenburger-San Saba	523	Draft Llano Uplift GAM	
Gillespie	Edwards-Trinity (Plateau)	Hickory	11	Draft Llano Uplift GAM	
Gillespie	Hickory	Ellenburger-San Saba	3,419	Draft Llano Uplift GAM	
Gillespie	Trinity	Edwards-Trinity (Plateau)	1,054	Edwards Trinity (Plateau) and Pecos Valley GAM v. 1.01	Different models show flow reversal
Gillespie	Trinity	Ellenburger-San Saba	57	Draft Llano Uplift GAM	
Glasscock	Edwards-Trinity (Plateau)	Ogallala	445	High Plains Aquifer System GAM v1.01	Different models show flow reversal
Glasscock	Ogallala	Edwards-Trinity (Plateau)	5,457	Edwards Trinity (Plateau) and Pecos Valley GAM v. 1.01	Different models show flow reversal

Table 5-2 (continued). Detailed modeled estimates of inter-aquifer flows between major and minor aquifers in Texas counties.

County	From aquifer	To aquifer	Average annual net flow (acre feet per year)	Groundwater availability model (GAM)	Comments
Hale	Dockum	Ogallala	254	High Plains Aquifer System GAM v1.01	
Hale	Ogallala	Edwards-Trinity (High Plains)	2,515	High Plains Aquifer System GAM v1.01	
Hall	Seymour	Blaine	644	Seymour Aquifer GAM v_1.01	
Hardeman	Blaine	Seymour	2,080	Seymour Aquifer GAM v_1.01	
Hartley	Ogallala	Rita Blanca	9	High Plains Aquifer System GAM v1.01	
Hartley	Ogallala	Dockum	644	High Plains Aquifer System GAM v1.01	
Hartley	Rita Blanca	Dockum	83	High Plains Aquifer System GAM v1.01	
Hays	Trinity	Edwards (Balcones Fault Zone)	3,192	Edwards (Balcones Fault Zone) San Antonio segment GAM	Different models show different average flux
Hays	Trinity	Edwards (Balcones Fault Zone)	17,265	Edwards Trinity (Plateau) and Pecos Valley GAM v. 1.01	Different models show different average flux
Hockley	Ogallala	Edwards-Trinity (High Plains)	721	High Plains Aquifer System GAM v1.01	
Howard	Edwards-Trinity (Plateau)	Dockum	48	High Plains Aquifer System GAM v1.01	
Irion	Dockum	Edwards-Trinity (Plateau)	4	High Plains Aquifer System GAM v1.01	

Table 5-2 (continued). Detailed modeled estimates of inter-aquifer flows between major and minor aquifers in Texas counties.

County	From aquifer	To aquifer	Average annual net flow (acre feet per year)	Groundwater availability model (GAM)	Comments
Irion	Edwards Trinity Plateau & Other Formations	Lipan	2,966	Lipan GAM v_1.01	
Jeff Davis	Edwards-Trinity (Plateau)	Pecos Valley	1,757	Edwards Trinity (Plateau) and Pecos Valley GAM v. 1.01	
Jones	Blaine	Seymour	323	Seymour Aquifer GAM v_1.01	
Kendall	Edwards-Trinity (Plateau)	Trinity	3,564	Edwards Trinity (Plateau) and Pecos Valley GAM v. 1.01	Different models show different average flux
Kendall	Edwards-Trinity (Plateau)	Trinity	1,139	Draft Llano Uplift GAM	Different models show different average flux
Kendall	Hickory	Ellenburger-San Saba	1,625	Draft Llano Uplift GAM	
Kent	Seymour	Blaine	335	Seymour Aquifer GAM v_1.01	
Kerr	Edwards-Trinity (Plateau)	Trinity	5,847	Edwards Trinity (Plateau) and Pecos Valley GAM v. 1.01	
Kerr	Hickory	Ellenburger-San Saba	215	Draft Llano Uplift GAM	
Kerr	Trinity	Edwards-Trinity (Plateau)	15,094	Draft Llano Uplift GAM	
Kimble	Edwards-Trinity (Plateau)	Marble Falls	6	Draft Llano Uplift GAM	
Kimble	Edwards-Trinity (Plateau)	Ellenburger-San Saba	34	Draft Llano Uplift GAM	
Kimble	Ellenburger-San Saba	Marble Falls	824	Draft Llano Uplift GAM	
Kimble	Hickory	Ellenburger-San Saba	3	Draft Llano Uplift GAM	

Table 5-2 (continued). Detailed modeled estimates of inter-aquifer flows between major and minor aquifers in Texas counties.

County	From aquifer	To aquifer	Average annual net flow (acre feet per year)	Groundwater availability model (GAM)	Comments
Kinney	Edwards-Trinity (Plateau)	Edwards (Balcones Fault Zone)	2,957	Edwards (Balcones Fault Zone) San Antonio segment GAM	Different models show different average flux
Kinney	Edwards-Trinity (Plateau)	Edwards (Balcones Fault Zone)	17,142	Edwards Trinity (Plateau) and Pecos Valley GAM v. 1.01	Different models show different average flux
Kinney	Edwards-Trinity (Plateau)	Edwards (Balcones Fault Zone)	11,115	Kinney County Alternative GAM	Different models show different average flux
Lamb	Edwards-Trinity (High Plains)	Ogallala	188	High Plains Aquifer System GAM v1.01	
Lampasas	Ellenburger-San Saba	Hickory	19	Draft Llano Uplift GAM	
Lampasas	Marble Falls	Ellenburger-San Saba	98	Draft Llano Uplift GAM	
Lampasas	Trinity	Marble Falls	37	Draft Llano Uplift GAM	
Lampasas	Trinity	Ellenburger-San Saba	1	Draft Llano Uplift GAM	
Llano	Ellenburger-San Saba	Hickory	9,271	Draft Llano Uplift GAM	
Lubbock	Edwards-Trinity (High Plains)	Ogallala	2,044	High Plains Aquifer System GAM v1.01	

Table 5-2 (continued). Detailed modeled estimates of inter-aquifer flows between major and minor aquifers in Texas counties.

County	From aquifer	To aquifer	Average annual net flow (acre feet per year)	Groundwater availability model (GAM)	Comments
Lynn	Ogallala	Edwards-Trinity (High Plains)	1,708	High Plains Aquifer System GAM v1.01	
Martin	Dockum	Ogallala	9	High Plains Aquifer System GAM v1.01	
Martin	Dockum	Edwards-Trinity (Plateau)	1	High Plains Aquifer System GAM v1.01	
Martin	Edwards-Trinity (Plateau)	Ogallala	771	Edwards Trinity (Plateau) and Pecos Valley GAM v. 1.01	
Martin	Ogallala	Edwards-Trinity (Plateau)	204	High Plains Aquifer System GAM v1.01	
Mason	Edwards-Trinity (Plateau)	Ellenburger-San Saba	342	Draft Llano Uplift GAM	
Mason	Edwards-Trinity (Plateau)	Hickory	32	Draft Llano Uplift GAM	
Mason	Hickory	Ellenburger-San Saba	49	Draft Llano Uplift GAM	
McCulloch	Edwards-Trinity (Plateau)	Marble Falls	1	Draft Llano Uplift GAM	
McCulloch	Edwards-Trinity (Plateau)	Ellenburger-San Saba	9	Draft Llano Uplift GAM	
McCulloch	Hickory	Ellenburger-San Saba	114	Draft Llano Uplift GAM	
McCulloch	Marble Falls	Ellenburger-San Saba	1,836	Draft Llano Uplift GAM	

Table 5-2 (continued). Detailed modeled estimates of inter-aquifer flows between major and minor aquifers in Texas counties.

County	From aquifer	To aquifer	Average annual net flow (acre feet per year)	Groundwater availability model (GAM)	Comments
Medina	Trinity	Edwards (Balcones Fault Zone)	7,468	Edwards (Balcones Fault Zone) San Antonio segment GAM	Different models show different average flux
Medina	Trinity	Edwards (Balcones Fault Zone)	28,617	Edwards Trinity (Plateau) and Pecos Valley GAM v. 1.01	Different models show different average flux
Menard	Edwards-Trinity (Plateau)	Ellenburger-San Saba	21	Draft Llano Uplift GAM	
Midland	Dockum	Edwards-Trinity (Plateau)	16	High Plains Aquifer System GAM v1.01	
Midland	Edwards-Trinity (Plateau)	Ogallala	3,838	Edwards Trinity (Plateau) and Pecos Valley GAM v. 1.01	
Midland	Ogallala	Edwards-Trinity (Plateau)	304	High Plains Aquifer System GAM v1.01	
Milam	Carrizo-Wilcox	Brazos River Alluvium	1,143	Carrizo-Wilcox GAM (central) v1.01	
Mills	Ellenburger-San Saba	Hickory	15	Draft Llano Uplift GAM	
Moore	Ogallala	Dockum	1,647	High Plains Aquifer System GAM v1.01	
Motley	Ogallala	Dockum	2,471	High Plains Aquifer System GAM v1.01	
Oldham	Ogallala	Dockum	3,720	High Plains Aquifer System GAM v1.01	
Other Areas	Seymour	Blaine	321	Seymour Aquifer GAM v_1.01	

Table 5-2 (continued). Detailed modeled estimates of inter-aquifer flows between major and minor aquifers in Texas counties.

County	From aquifer	To aquifer	Average annual net flow (acre feet per year)	Groundwater availability model (GAM)	Comments
Parmer	Dockum	Ogallala	238	High Plains Aquifer System GAM v1.01	
Pecos	Edwards-Trinity (Plateau)	Pecos Valley	41,395	Edwards Trinity (Plateau) and Pecos Valley GAM v. 1.01	Different models show different average flux
Pecos	Edwards-Trinity (Plateau)	Pecos Valley	602	High Plains Aquifer System GAM v1.01	Different models show different average flux
Pecos	Edwards-Trinity (Plateau)	Dockum	925	High Plains Aquifer System GAM v1.01	
Pecos	Rustler	Dockum	1	Rustler GAM v1.01	
Potter	Ogallala	Dockum	1,345	High Plains Aquifer System GAM v1.01	
Randall	Ogallala	Dockum	2,757	High Plains Aquifer System GAM v1.01	
Reagan	Dockum	Edwards-Trinity (Plateau)	175	High Plains Aquifer System GAM v1.01	
Real	Trinity	Edwards-Trinity (Plateau)	272	Edwards Trinity (Plateau) and Pecos Valley GAM v. 1.01	
Reeves	Edwards-Trinity (Plateau)	Pecos Valley	44,182	Edwards Trinity (Plateau) and Pecos Valley GAM v. 1.01	Different models show flow reversal

Table 5-2 (continued). Detailed modeled estimates of inter-aquifer flows between major and minor aquifers in Texas counties.

County	From aquifer	To aquifer	Average annual net flow (acre feet per year)	Groundwater availability model (GAM)	Comments
Reeves	Edwards-Trinity (Plateau)	Dockum	440	High Plains Aquifer System GAM v1.01	
Reeves	Pecos Valley	Edwards-Trinity (Plateau)	532	High Plains Aquifer System GAM v1.01	Different models show flow reversal
Robertson	Carrizo-Wilcox	Brazos River Alluvium	1,218	Carrizo-Wilcox GAM (central) v1.01	
Runnels	Edwards Trinity Plateau & Other Formations	Lipan	2,185	Lipan GAM v_1.01	
San Saba	Hickory	Ellenburger-San Saba	4,446	Draft Llano Uplift GAM	
San Saba	Marble Falls	Ellenburger-San Saba	1,713	Draft Llano Uplift GAM	
Schleicher	Edwards Trinity Plateau & Other Formations	Lipan	395	Lipan GAM v_1.01	
Sherman	Ogallala	Dockum	62	High Plains Aquifer System GAM v1.01	
Sterling	Edwards-Trinity (Plateau)	Dockum	566	High Plains Aquifer System GAM v1.01	
Stonewall	Seymour	Blaine	915	Seymour Aquifer GAM v_1.01	
Swisher	Ogallala	Dockum	1,596	High Plains Aquifer System GAM v1.01	
Terry	Ogallala	Edwards-Trinity (High Plains)	449	High Plains Aquifer System GAM v1.01	
Tom Green	Edwards-Trinity (Plateau)	Dockum	9	High Plains Aquifer System GAM v1.01	

Table 5-2 (continued). Detailed modeled estimates of inter-aquifer flows between major and minor aquifers in Texas counties.

County	From aquifer	To aquifer	Average annual net flow (acre feet per year)	Groundwater availability model (GAM)	Comments
Tom Green	Lipan	Edwards-Trinity (Plateau) & Other Formations	2,967	Lipan GAM v_1.01	
Travis	Edwards (Balcones Fault Zone)	Trinity	12,403	Edwards Trinity (Plateau) and Pecos Valley GAM v. 1.01	Different models show different average flux
Travis	Edwards (Balcones Fault Zone)	Trinity	3,172	Northern Trinity Woodbine GAM v2.01	Different models show different average flux
Travis	Trinity	Edwards (Balcones Fault Zone)	1,072	Edwards (Balcones Fault Zone) San Antonio segment	
Upton	Dockum	Edwards-Trinity (Plateau)	358	High Plains Aquifer System GAM v1.01	
Upton	Pecos Valley	Edwards-Trinity (Plateau)	228	Edwards Trinity (Plateau) and Pecos Valley GAM v. 1.01	
Uvalde	Edwards-Trinity (Plateau)	Edwards (Balcones Fault Zone)	9,604	Edwards (Balcones Fault Zone) San Antonio segment GAM	Different models show different average flux
Uvalde	Edwards-Trinity (Plateau)	Edwards (Balcones Fault Zone)	20,838	Edwards Trinity (Plateau) and Pecos Valley GAM v. 1.01	Different models show different average flux

Table 5-2 (continued). Detailed modeled estimates of inter-aquifer flows between major and minor aquifers in Texas counties.

County	From aquifer	To aquifer	Average annual net flow (acre feet per year)	Groundwater availability model (GAM)	Comments
Uvalde	Trinity	Edwards (Balcones Fault Zone)	1,616	Edwards (Balcones Fault Zone) San Antonio segment GAM	Different models show different average flux
Uvalde	Trinity	Edwards-Trinity (Plateau)	3,649	Edwards Trinity (Plateau) and Pecos Valley GAM v. 1.01	
Uvalde	Trinity	Edwards (Balcones Fault Zone)	6,664	Edwards Trinity (Plateau) and Pecos Valley GAM v. 1.01	Different models show different average flux
Williamson	Edwards (Balcones Fault Zone)	Trinity	1,242	Northern Trinity Woodbine GAM v2.01	
Winkler	Edwards-Trinity (Plateau)	Dockum	20	High Plains Aquifer System GAM v1.01	
Winkler	Ogallala	Pecos Valley	38	High Plains Aquifer System GAM v1.01	
Winkler	Ogallala	Dockum	6	High Plains Aquifer System GAM v1.01	
Winkler	Pecos Valley	Edwards-Trinity (Plateau)	0	Edwards Trinity (Plateau) and Pecos Valley GAM v1.01	
Yoakum	Ogallala	Edwards-Trinity (High Plains)	2,119	High Plains Aquifer System GAM v1.01	
Other Areas	Lipan	Edwards-Trinity (Plateau) & Other Formations	1,873	Lipan GAM v_1.01	

6 Aquifer Summaries

Aquifers summaries are listed below alphabetically in major and minor categories. These summaries are derived from TWDB databases, reports, and maps, TWDB groundwater availability modeling studies, and scientific studies from outside institutions.

Each aquifer summary includes a snapshot of the geology and hydrogeology, flows to surface water and other aquifers, water quantity, and water quality.

Major Aquifers

Minor Aquifers

6.1 *Carrizo-Wilcox Aquifer*

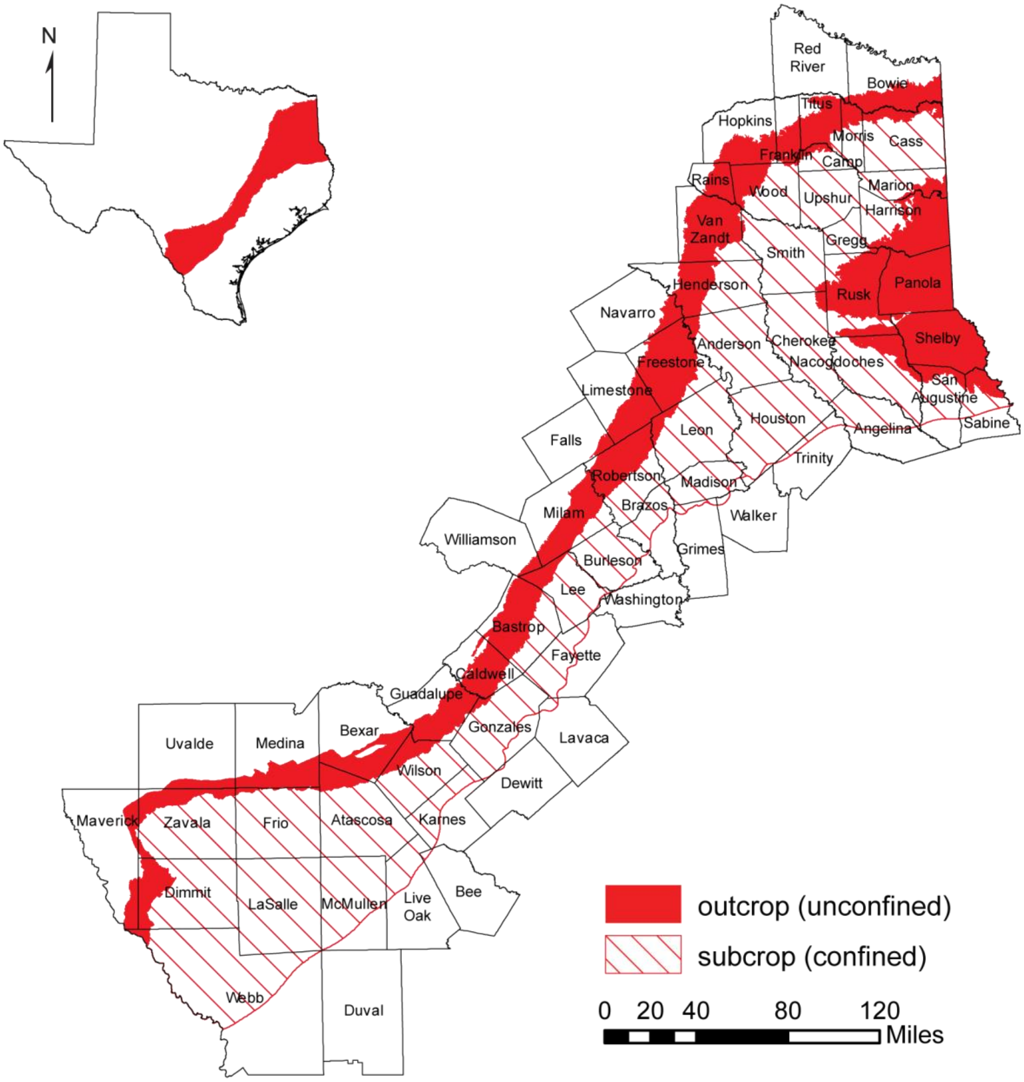


Figure 6-1. **Extent of the Carrizo-Wilcox Aquifer, showing the unconfined (outcrop) and confined (subsurface) areas.**

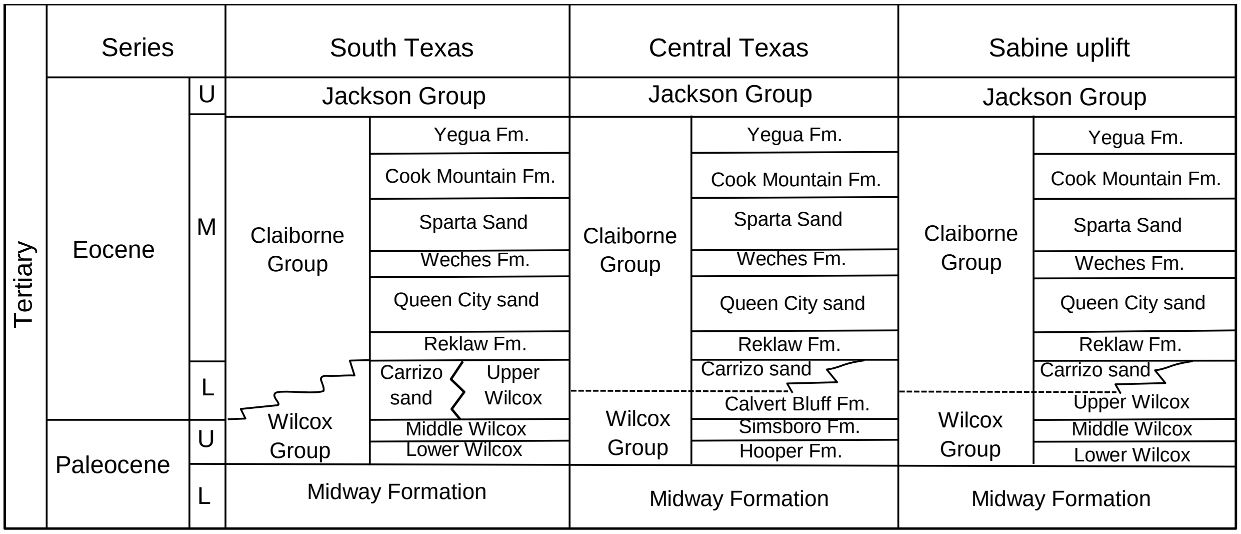
Aquifer characteristics

- Aquifer type: confined and unconfined
- Area of outcrop: 11,227 square miles
- Area of subsurface: 25,491 square miles
- Proportion of aquifer with groundwater conservation districts: 65 percent
- Number of counties containing the aquifer: 66

Geology and hydrogeology

The Carrizo-Wilcox Aquifer is a major aquifer extending from the Louisiana border to the Mexico border in a wide band adjacent to and northwest of the Gulf Coast Aquifer (Figure 6-1). It consists of the Hooper, Simsboro, and Calvert Bluff formations of the Wilcox Group and the overlying Carrizo Formation of the Claiborne Group. The aquifer is 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 670 feet.

The Carrizo-Wilcox Aquifer is unconfined in the outcrop area. The aquifer is confined in the down-dip region where it is overlain by the lower-permeability Reklaw Formation. Figure 6-2 summarizes the stratigraphic and hydrogeologic units of the aquifer. In general, the Simsboro and Carrizo formations contain thicker, more laterally continuous and more permeable sands and, therefore, are more important hydrostratigraphic units when determining groundwater availability. The Calvert Bluff and Hooper formations typically are made up of clay, silt, and sand mixtures, as well as lignite deposits. Because of their relatively low vertical permeability, the Hooper and Calvert Bluff formations act as leaky aquitards that confine fluid pressures in the Simsboro and Carrizo aquifers and restrict groundwater movement between the layers. Although the Hooper and Calvert Bluff formations contain sand units, they are generally finer and less continuous than the sands of the Simsboro and Carrizo formations (Hutchison and others, 2009).



	Series		South Texas		Central Texas		Sabine uplift	
Tertiary	Eocene	U	Jackson Group		Jackson Group		Jackson Group	
		M	Claiborne Group	Yegua Fm.	Claiborne Group	Yegua Fm.	Claiborne Group	Yegua Fm.
				Cook Mountain Fm.		Cook Mountain Fm.		Cook Mountain Fm.
				Sparta Sand		Sparta Sand		Sparta Sand
				Weches Fm.		Weches Fm.		Weches Fm.
				Queen City sand		Queen City sand		Queen City sand
				Reklaw Fm.		Reklaw Fm.		Reklaw Fm.
		L		Carrizo sand Upper Wilcox		Carrizo sand		Carrizo sand
			Wilcox Group		Wilcox Group	Calvert Bluff Fm.	Wilcox Group	Upper Wilcox
	Paleocene	U		Middle Wilcox		Simsboro Fm.		Middle Wilcox
				Lower Wilcox		Hooper Fm.		Lower Wilcox
		L	Midway Formation		Midway Formation		Midway Formation	

Figure 6-2. **Stratigraphy and hydrogeology in the Carrizo-Wilcox Aquifer (modified from Mace and others, 2000).** ***(Fm = Formation; U = Upper; M = Middle; L = Lower)***

The marine deposits of the Paleocene Midway Formation are the lower confining boundary of the Carrizo-Wilcox Aquifer. The Eocene Reklaw Formation represents a semi-confining unit between the Carrizo Sand and the shallower Queen City Aquifer. In the northeastern part of the aquifer the Reklaw clays become discontinuous, providing a more permeable connection between the Carrizo Sand and the overlying Queen City Formation. The Wilcox Fault Zone, a series of growth faults caused by sediment progradation onto marine clays and resulting basin-ward slippage and subsidence, defines the down-dip limit of the aquifer. Figure 6-3 shows structural cross-sections for the southern and northern portions of the aquifer.

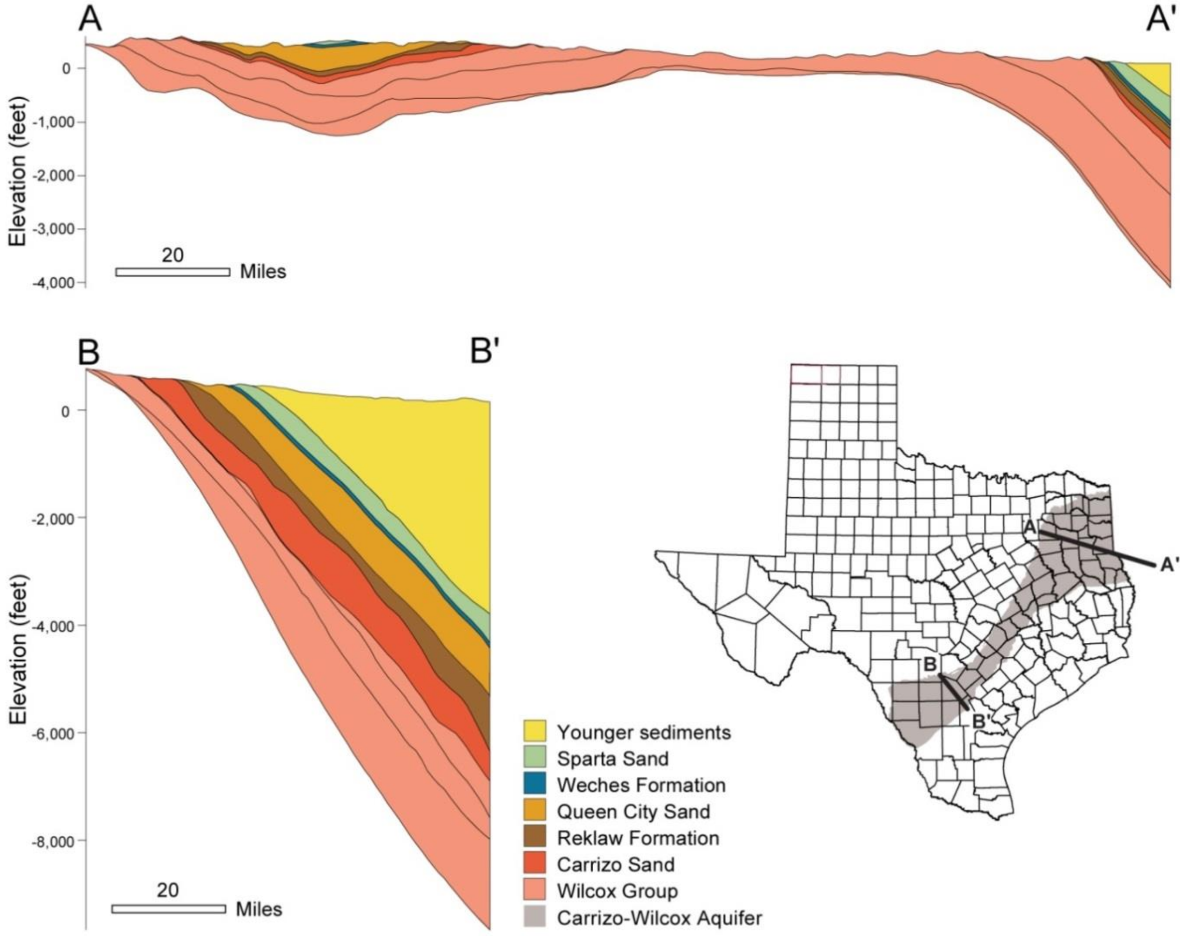


Figure 6-3. **Structural cross-sections of the Carrizo-Wilcox Aquifer and overlying strata (modified from Kelley and others, 2004).**

The mean hydraulic conductivity of the Carrizo-Wilcox Aquifer generally decreases to the northeast. Hydraulic conductivity ranges from about 0.01 to 4,000 feet per day and has a mean of about 6 feet per day. Transmissivity ranges from about 0.1 to 10,000 feet squared per day and has a geometric mean of about 300 feet squared per day. The Simsboro Formation and Carrizo

Sand portions of the Carrizo-Wilcox Aquifer have higher transmissivity and hydraulic conductivity than the Cypress Aquifer, Calvert Bluff Formation, and undivided Wilcox Group. The highest transmissivity and hydraulic conductivity for the Carrizo Formation is in the Winter Garden area. The highest transmissivity and hydraulic conductivity for the Wilcox Group is in the south central and northeast parts of the aquifer.

Flows to surface water and other aquifers

Groundwater discharges to local creeks and major streams crossing the unconfined area of the aquifer when the water level in the aquifer is higher than the stream. Conversely, stream water may recharge the aquifer during flood events when the stream is high or when pumping draws down the water level in the aquifer. Flows from the Carrizo-Wilcox Aquifer to surface-water bodies (Table 6-1), are estimated from stream baseflow and surface runoff measurements.

In general, the low-permeability geological units above and below the Carrizo-Wilcox Aquifer strongly limit inter-aquifer flow. The aquifer also has limited areas of overlap with other major or minor aquifers where freshwater flow could potentially occur. In these areas of potential communication, the direction and magnitude of any inter-aquifer flow depends on the hydraulic conductivity of the intervening formations and the potentiometric head differences between the aquifers.

In most of the groundwater availability models developed by the TWDB, the upper and lower boundaries of the Carrizo-Wilcox Aquifer are specified as no-flow surfaces, based on the conceptual model that any inter-aquifer flows that might occur are several orders of magnitude smaller than flows within the aquifer and are not significant on a regional scale.

Table 6-2 shows estimated flows from the Carrizo-Wilcox Aquifer to other major and minor aquifers, as calculated by approved TWDB models. The only inter-aquifer flow that is calculated by the models is the flow between the Carrizo-Wilcox and the Brazos River Alluvium aquifers. The Queen City Aquifer is present above the Carrizo-Wilcox Aquifer over much of its extent and, as noted above, has potential for inter-aquifer flow to the northeast where the Reklaw Formation clays become thin or discontinuous, but the model for the northern Carrizo-Wilcox Aquifer does not expressly calculate these potential flows.

Brackish and saline groundwater is present in the down-dip regions of the Carrizo-Wilcox Aquifer. The Carrizo and Wilcox sands become oil-producing reservoir rocks in the Gulf Coast region, where they are present at depths of several thousand feet beneath the Gulf Coast Aquifer. Growth faults along the Wilcox Fault Zone limit down-dip movement of freshwater into the brackish and saline zones beyond the established extent of the Carrizo-Wilcox Aquifer.

Table 6-1. Summary of groundwater flow from the Carrizo-Wilcox Aquifer to surface water, by county.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Anderson	47	2.7	0.6
Atascosa	143	12.9	4.5
Bastrop	462	24.1	4.2
Bexar	366	41.3	16.4
Bowie	359	78.1	18.1
Burleson	0	0	0
Caldwell	299	27.7	6.4
Camp	35	5.9	1.3
Cass	131	38.1	9.6
Cherokee	29	10.3	3.8
Dimmit	256	3.8	0.9
Falls	44	2.3	0.2
Franklin	147	24.4	5.5
Freestone	676	59.5	11.9
Frio	26	1.2	0.4
Gonzales	21	3.2	1.1
Gregg	8	2.4	0.7
Guadalupe	362	27.1	8.2
Harrison	526	124.1	29.4
Henderson	309	40.1	13
Hopkins	279	35.8	6.4
Lee	107	4.9	0.8
Leon	66	3.6	0.3
Limestone	338	18.4	1.6
Marion	82	24.4	7.2
Maverick	189	4	1
Medina	342	19.8	6.5
Milam	425	32.3	4
Morris	80	19.1	3.9
Nacogdoches	184	61.9	22
Navarro	101	6.5	1.1
Panola	816	144.3	27.9
Rains	166	18.8	2.7
Red River	6	0.9	0.1

Table 6-1 (continued). Summary of groundwater flow from the Carrizo-Wilcox Aquifer to surface water, by county.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Robertson	390	25.5	2.5
Rusk	646	198.1	65.2
Sabine	117	26	5.1
San Augustine	98	25.2	6.2
Shelby	817	148.7	24.8
Smith	15	4	1.3
Titus	296	60.2	12.1
Uvalde	118	3.9	0.8
Van Zandt	574	61	11.2
Webb	22	0.3	0.1
Williamson	39	2.1	0.3
Wilson	143	10.9	4
Wood	198	25	4.2
Zavala	255	7.6	1.7
Total	**11,155**	**1,522**	**361**

Table 6-2. Flow between the Carrizo-Wilcox and Brazos River Alluvium aquifers.

Flow from	Flow to	Total flow (acre-feet per year)
Carrizo-Wilcox Aquifer	Brazos River Alluvium Aquifer	2,361

Water quantity

Total storage in the Carrizo-Wilcox Aquifer is estimated to be about 5.2 billion acre-feet. Recoverable storage is estimated to be between 25 and 75 percent of the total, about 1.3 billion to 3.9 billion acre-feet (Table 6-3).

Figure 6-4 shows changes in water levels in the Carrizo-Wilcox Aquifer from 1995 to 2015. Most of the aquifer shows increased water levels as a result of recharge during the period from 2000 to 2005. Starting around 2005, the southernmost portion of the aquifer has experienced increasing drawdown, which may be correlated with the expansion of oil field activity in the Eagle Ford Shale and other formations in the area.

Table 6-3. Total estimated recoverable storage in the Carrizo-Wilcox Aquifer, by groundwater management area, in acre-feet.

Groundwater management area	Total storage	25 percent of storage	75 percent of storage
11	2,061,633,000	515,408,250	1,546,224,750
12	1,019,320,000	254,830,000	764,490,000
13	1,951,720,000	487,930,000	1,463,790,000
14	19,804,000	4,951,000	14,853,000
15	69,900,000	17,475,000	52,425,000
16	104,700,000	26,175,000	78,525,000
Total	**5,227,077,000**	**1,306,769,250**	**3,920,307,750**

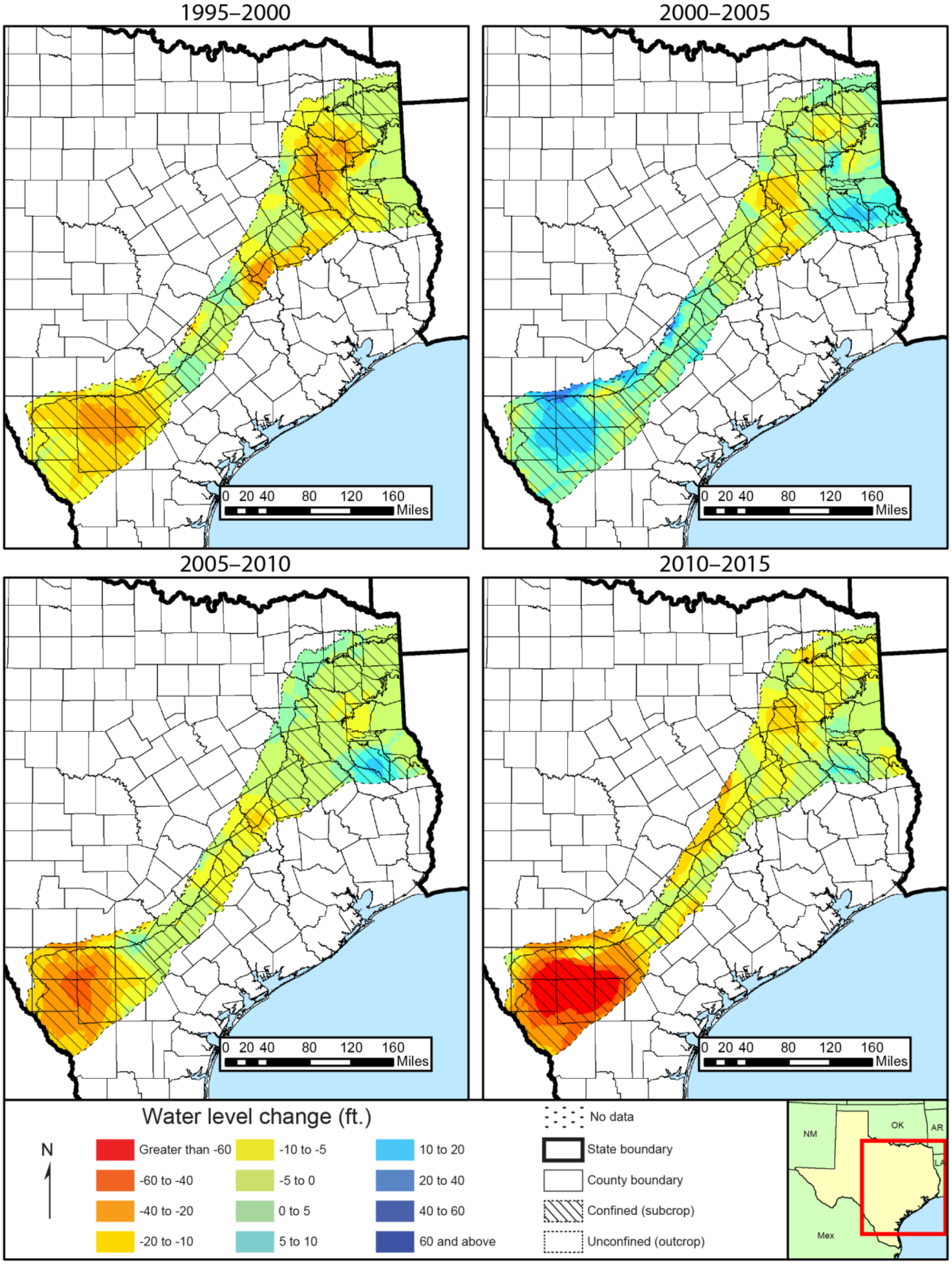


Figure 6-4. Water-level changes in the Carrizo-Wilcox Aquifer, 1995 to 2015.

Water quality

Water quality in the Carrizo-Wilcox Aquifer (Figure 6-5) shows isolated areas of slightly saline to moderately saline groundwater in the eastern and central portions of the aquifer and more widespread areas of slightly to moderately saline groundwater in the southwest. Groundwater in the unconfined area is hard and typically has total dissolved solids concentrations less than 1,000 milligrams per liter. Groundwater in the confined area of the aquifer is generally softer and has total dissolved solids concentrations less than 1,000 milligrams per liter except in the southern and western portions of the aquifer. Parts of the aquifer in the Winter Garden area and in parts of Brazos County are slightly to moderately saline, with total dissolved solids concentrations ranging from 1,000 to 7,000 milligrams per liter.

High iron and manganese content in excess of secondary drinking water standards is characteristic of the deeper subsurface portions of the aquifer. Radionuclides are found at concentrations exceeding drinking water standards in limited areas in the south and central outcrop regions (Reedy and others, 2011).

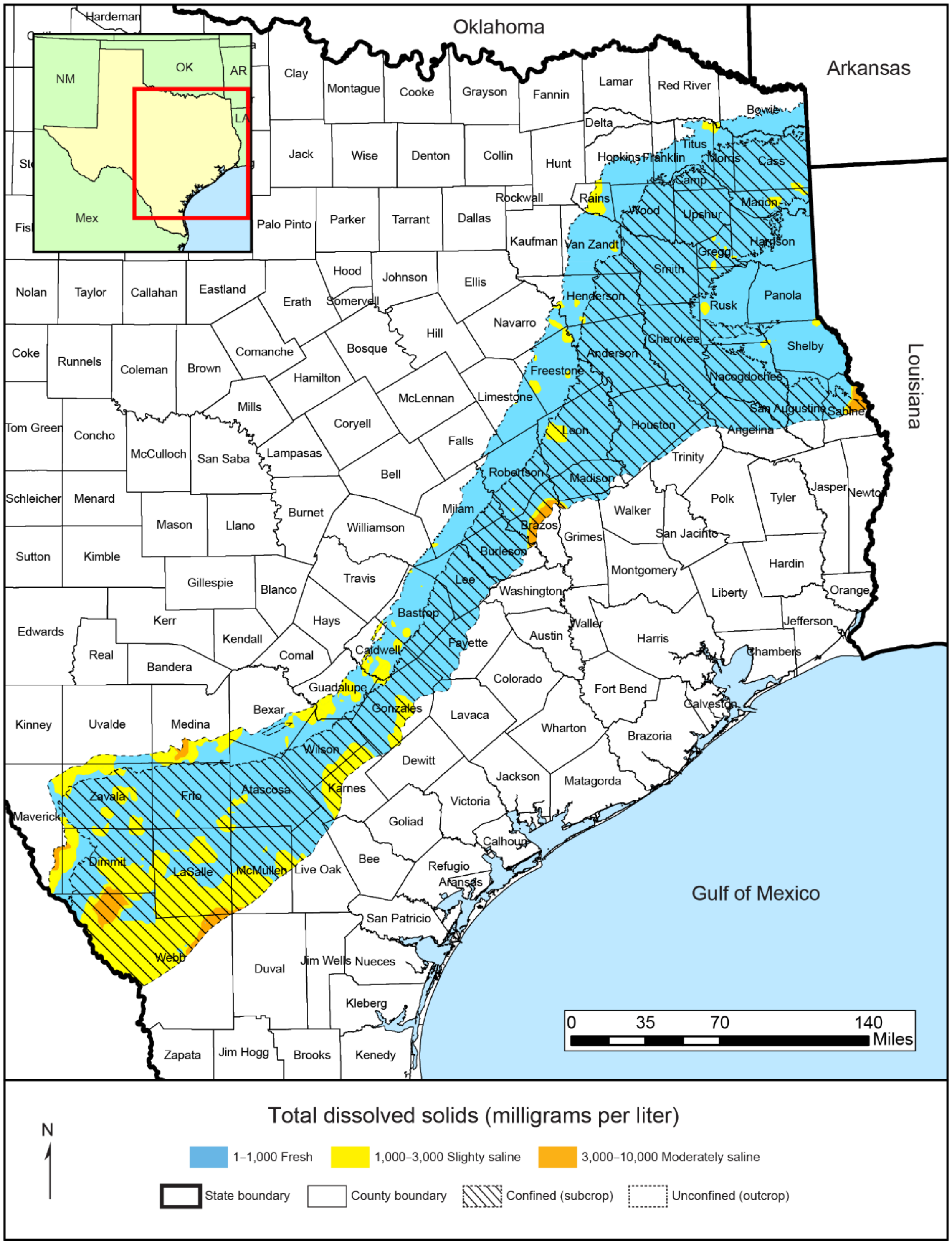


Figure 6-5. Total dissolved solids in the Carrizo-Wilcox Aquifer.

6.2 Edwards (Balcones Fault Zone) Aquifer

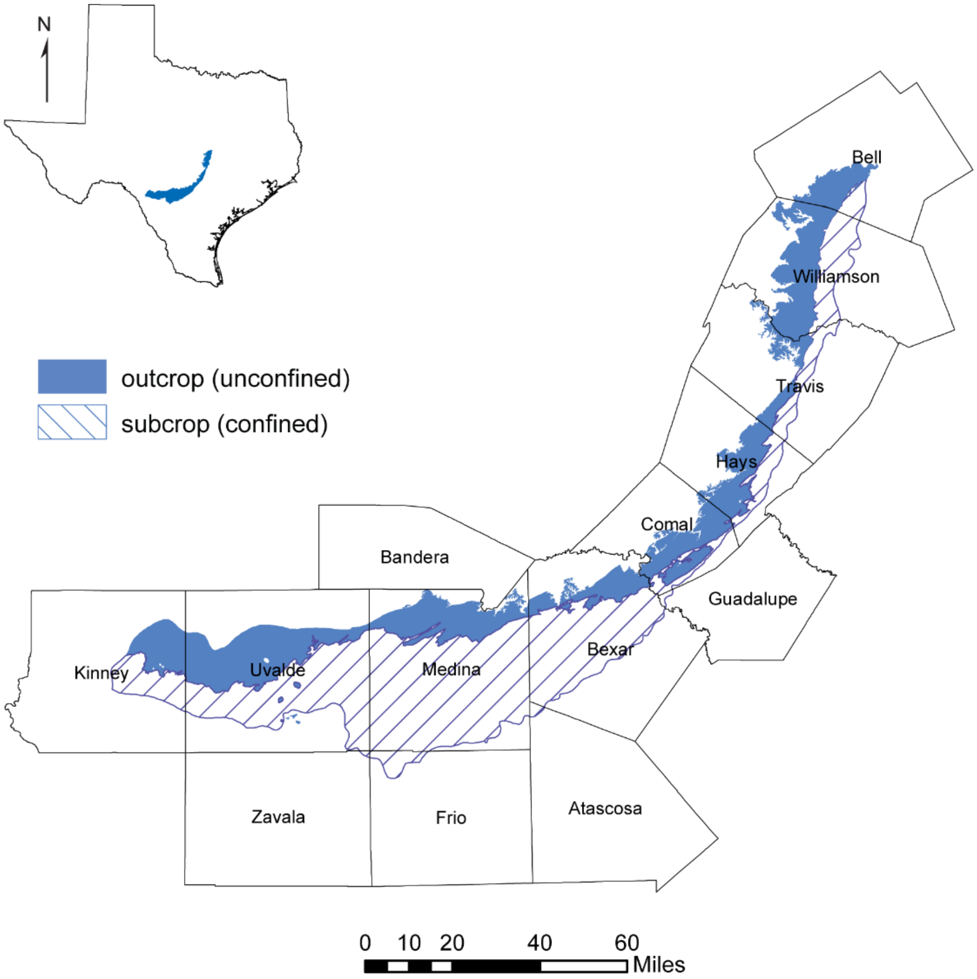


Figure 6-6. Extent of the Edwards (Balcones Fault Zone) Aquifer.

Aquifer characteristics

- Aquifer type: confined and unconfined
- Area of outcrop: 1,566 square miles
- Area in subsurface: 2,481 square miles
- Proportion of aquifer with groundwater conservation districts: 87 percent
- Number of counties containing the aquifer: 14

Geology and hydrogeology

The Edwards (Balcones Fault Zone) Aquifer is a major aquifer in the south central part of the state (Figure 6-6). It 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.

The Edwards (Balcones Fault Zone) Aquifer is part of an aquifer system developed in thick and regionally extensive Lower Cretaceous carbonates that underlie large areas of Texas. The carbonates in the Edwards (Balcones Fault Zone) Aquifer are laterally and vertically heterogeneous. The stratigraphy and hydrogeology of the aquifer are outlined in Figure 6-7 and Figure 6-8. The Edwards (Balcones Fault Zone) Aquifer consists of highly permeable rocks, where water flows through faults, fractures, joints, and conduits.

The Edwards (Balcones Fault Zone) Aquifer is unconfined in the outcrop area. In the down-dip area the aquifer is confined by the overlying Del Rio Clay. The Glen Rose Limestone, which is the uppermost unit of the Trinity Aquifer, generally defines the lower boundary of the aquifer. The degree of hydraulic connection between the Trinity and Edwards (Balcones Fault Zone) aquifers is locally limited by the relatively low vertical hydraulic conductivities of the basal Edwards and upper Trinity units, but on a regional scale karstic features allow cross-formational flow to occur (Lindgren and others, 2004).

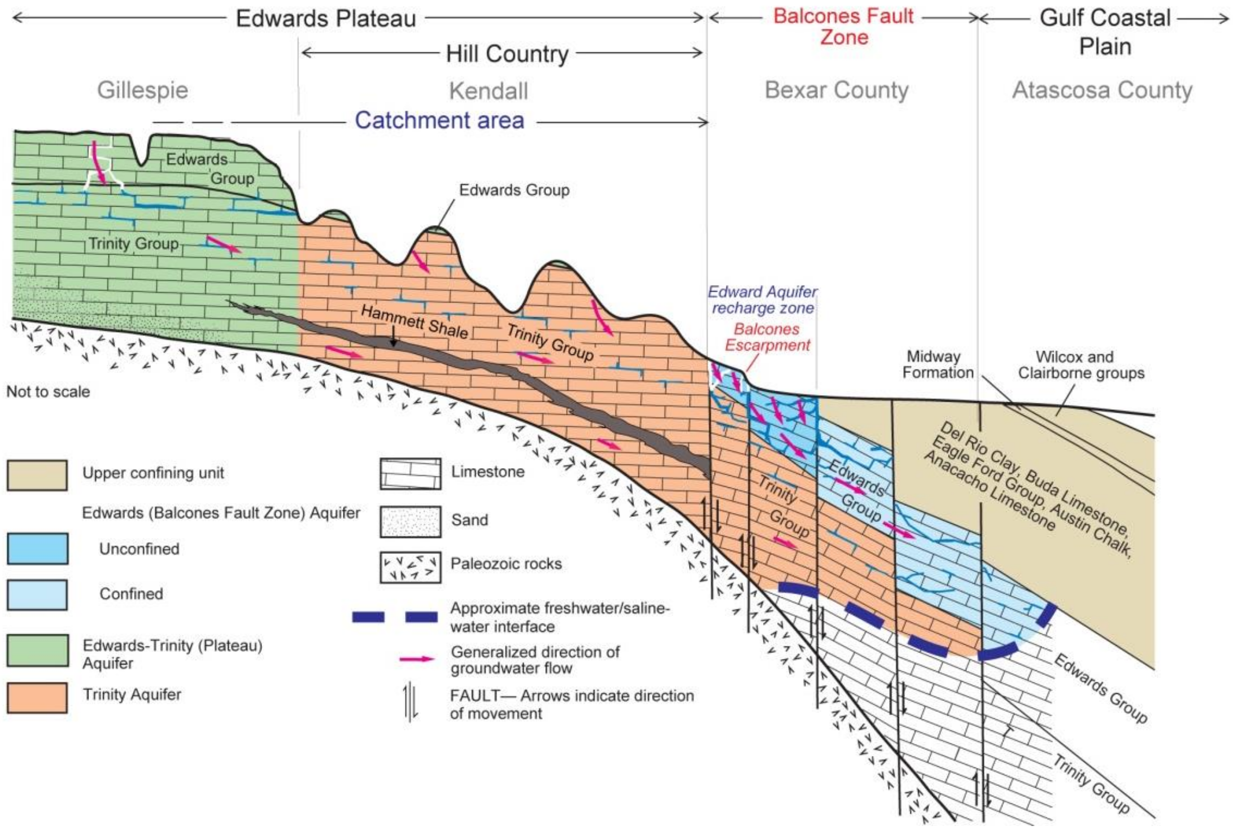


Figure 6-7. **Diagrammatic cross-section showing hydrogeologic framework and generalized groundwater flow through the Edwards (Balcones Fault Zone) Aquifer, San Antonio region, Texas (modified from Barker and Ardis, 1996; Lindgren and others, 2004).**

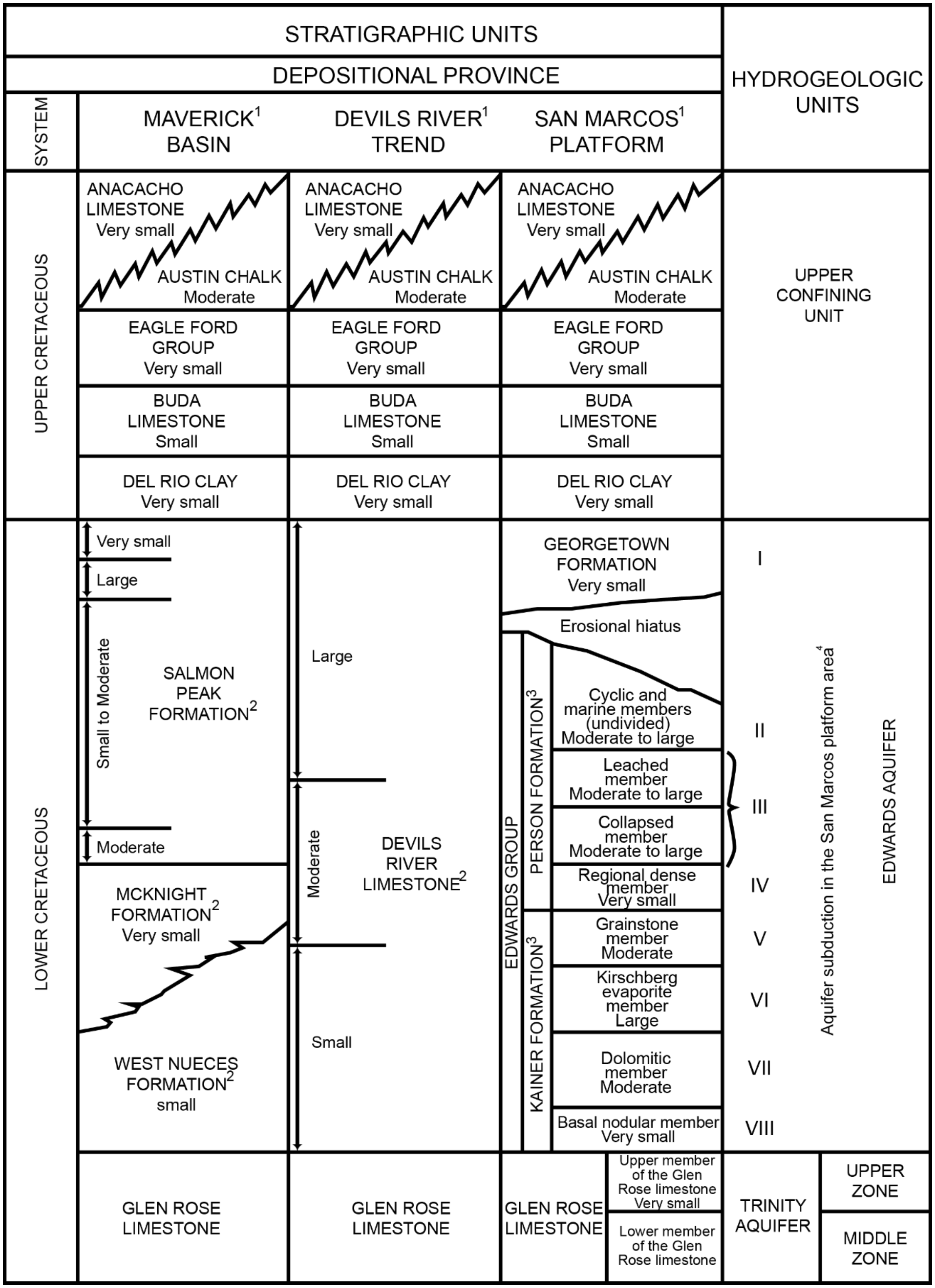


Figure 6-8. Hydrostratigraphy of the Edwards (Balcones Fault Zone) Aquifer (modified from Lindgren and others, 2004).

Flows to surface water and other aquifers

The Edwards (Balcones Fault Zone) Aquifer feeds several well-known springs, including Comal Springs in Comal County, which is the largest spring in the state, and San Marcos Springs in Hays County, which is the second largest. Hueco, San Pedro, San Antonio, and Leona springs also discharge from the aquifer. Table 6-4 shows flows from the Edwards (Balcones Fault Zone) Aquifer to surface-water bodies, as estimated from stream baseflow and surface runoff measurements.

Table 6-5 shows the amount of springflow that makes up baseflow. Because of the aquifer's highly permeable nature, water levels and springflows respond quickly to rainfall, drought, and pumping. Although water levels in wells throughout the aquifer decline rapidly in response to drought conditions, they also rebound quickly with adequate rainfall.

Table 6-6 shows flow between the Edwards (Balcones Fault Zone) Aquifer and the Trinity and Edwards-Trinity (Plateau) aquifers. Groundwater availability models indicate flow both from the Edwards (Balcones Fault Zone) Aquifer into the Trinity Aquifer in some locations and from the Trinity Aquifer into the Edwards (Balcones Fault Zone) Aquifer in others.

Table 6-4. Summary of groundwater flow from the Edwards (Balcones Fault Zone) Aquifer to surface water, by county.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Bandera	0	0	0
Bell	93	7.7	1.3
Bexar	118	7.6	2.4
Comal	168	315.4	316.7
Hays	149	180.3	150.7
Kinney	118	4.5	1.5
Medina	234	22.4	5.8
Travis	81	71.4	58.6
Uvalde	351	35.3	12.4
Williamson	254	27.9	4.2
Total	**1,566**	**673**	**554**

Table 6-5. Summary of springflow from the Edwards (Balcones Fault Zone) Aquifer to surface water.

County	Sum of average annual springflow (cubic feet per second)	Sum of median annual springflow (cubic feet per second)	Spring names
Comal	296.1	311	Comal Springs at New Braunfels, TX San Marcos Springs at San Marcos, TX
Hays	156	146	San Marcos Springs at San Marcos, TX
Travis	60.7	58	Barton Springs at Austin, TX

Note: Springflow values are included as part of the total baseflow presented in Table 6-4.

Table 6-6. Model estimates of inter-aquifer flows between the Edwards (Balcones Fault Zone) Aquifer and other major aquifers.

Flow from	Flow to	Total flow (acre-feet per year)
Edwards (Balcones Fault Zone) Aquifer	Trinity Aquifer	9,381
Edwards-Trinity (Plateau) Aquifer	Edwards (Balcones Fault Zone) Aquifer	25,626
Trinity Aquifer	Edwards (Balcones Fault Zone) Aquifer	61,463

Water quantity

Total storage in the Edwards (Balcones Fault Zone) Aquifer is estimated to be more than 24 million acre-feet. Recoverable storage is estimated to be between 25 and 75 percent of the total, about 6.2 million to 18.7 million acre-feet (Table 6-7). Figure 6-9 shows changes in water levels in the Edwards (Balcones Fault Zone) Aquifer from 1995 to 2015.

The quantity of water that can be withdrawn from the aquifer within the Edwards Aquifer Authority jurisdiction is limited by law to be no more than 572,000 acre-feet per year to preserve the habitat for endangered species dependent on springflow from the aquifer. Counties within the Edwards Aquifer Authority's jurisdiction include all of Uvalde, Medina, and Bexar counties, and parts of Atascosa, Comal, Guadalupe, Caldwell, and Hays counties.

Table 6-7. Total estimated recoverable storage in the Edwards (Balcones Fault Zone) Aquifer, by groundwater management area, in acre-feet.

Groundwater management area	Total storage	25 percent of storage	75 percent of storage
8	94,900	23,725	71,175
9	260,700	65,175	195,525
10	22,877,900	5,719,475	17,158,425
13	1,718,400	429,600	1,288,800
Total	**24,951,900**	**6,237,975**	**18,713,925**

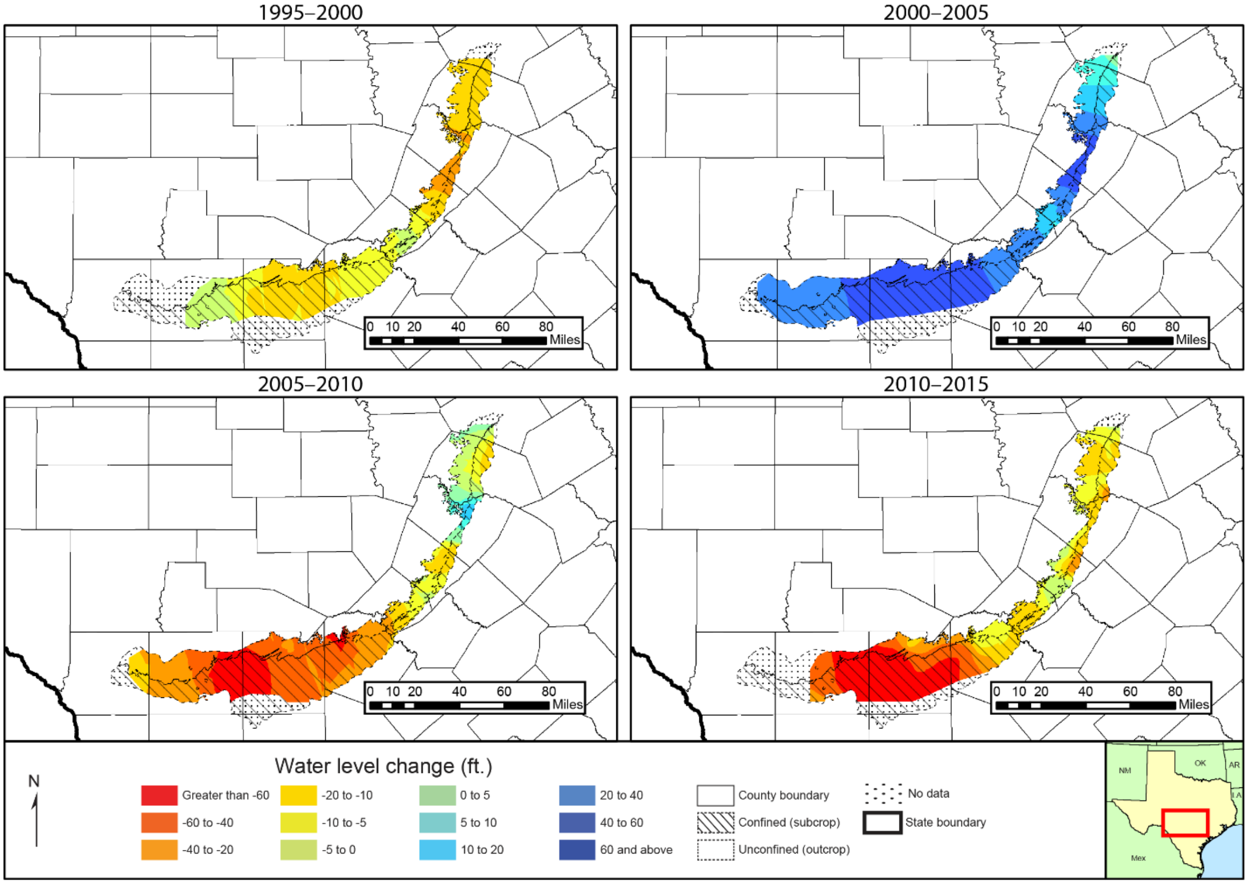


Figure 6-9. Water-level changes in the Edwards (Balcones Fault Zone) Aquifer, 1995 to 2015.

Water quality

Water quality in the aquifer is generally very good. The groundwater is hard but fresh and contains less than 500 milligrams per liter of total dissolved solids. Small regions of elevated fluoride are present in the northern Barton Springs segment and gross alpha radiation in the southern San Antonio segment of the aquifer (Reedy and others, 2011).

A map of the distribution of total dissolved solids in the Edwards (Balcones Fault Zone) Aquifer (Figure 6-10) shows freshwater in the unconfined area to the north and west of the Balcones Fault Zone and more saline water in the confined zone to the south and east, largely outside the official aquifer boundary. The rapid recharge and flow through karstic features results in a low residence time for water in the unconfined zone, limiting water-rock interactions that increase total dissolved solids. In the down-dip area the official boundary of the aquifer is largely determined by the extent of freshwater along the so-called “bad water line.” East and south of the “bad water line,” increased residence time and water interaction with evaporite members of the Edwards Formation result in increased groundwater salinity. The Edwards Formation continues laterally beyond the official aquifer boundary to the south and east, becoming highly saline with greater depth. The rapid recharge through the karstic outcrop increases the aquifer’s vulnerability to contamination, making nonpoint source pollution from runoff in urbanized areas a particular concern.

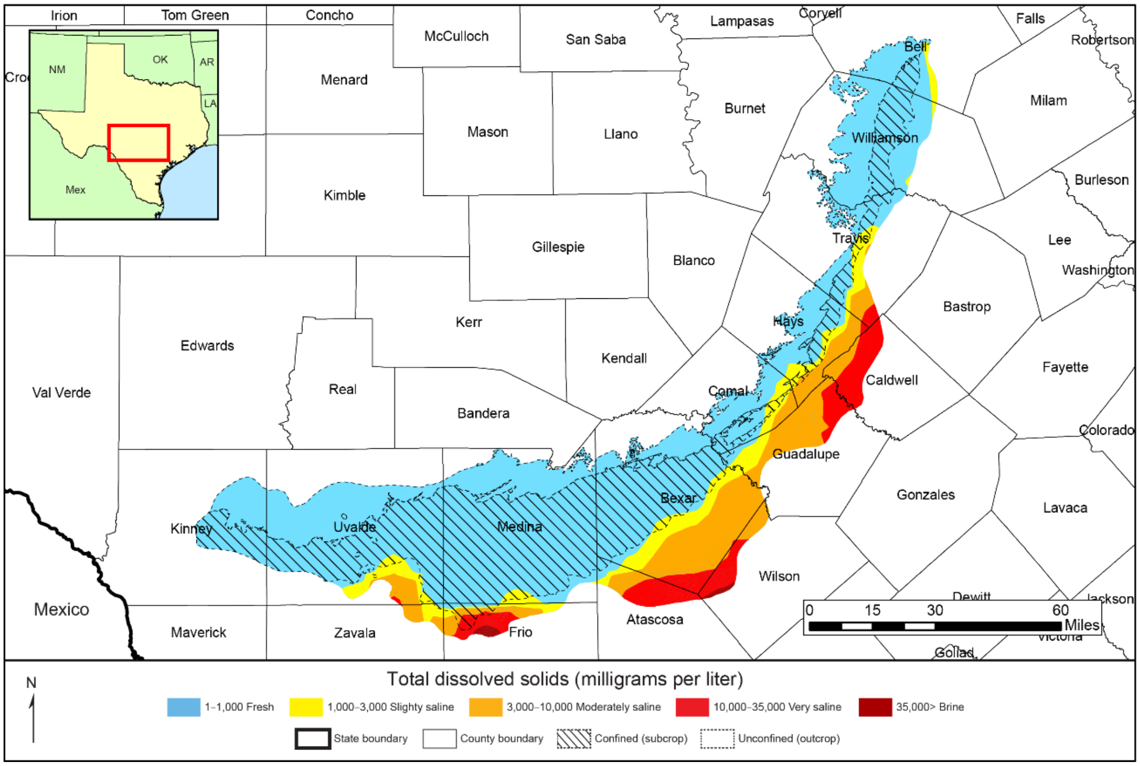


Figure 6-10. Total dissolved solids in the Edwards (Balcones Fault Zone) Aquifer.

6.3 *Edwards-Trinity (Plateau) Aquifer*

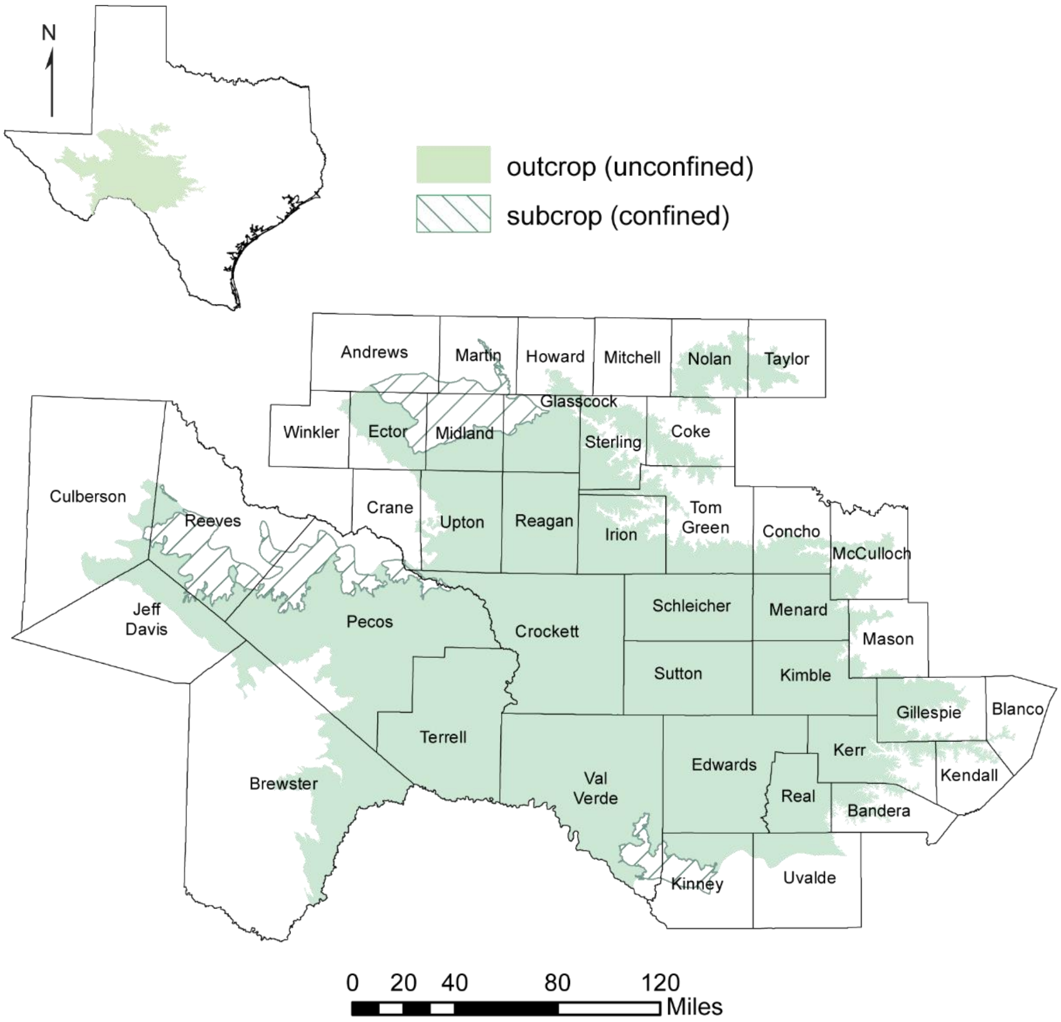


Figure 6-11. **Extent of the Edwards-Trinity (Plateau) Aquifer, showing unconfined (outcrop) and confined (subsurface) areas.**

Aquifer characteristics

- Aquifer type: mostly unconfined with small confined areas
- Area of outcrop: 32,373 square miles
- Area in subsurface: 3,051 square miles
- Proportion of aquifer with groundwater conservation districts: 82 percent
- Number of counties containing the aquifer: 41

Geology and hydrogeology

The Edwards-Trinity (Plateau) Aquifer is a major aquifer extending across much of the southwestern part of the state (Figure 6-11). The water-bearing units are composed predominantly of 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).

The aquifer is composed of Early Cretaceous-age sediments of the Trinity, Fredericksburg, and Lower Washita groups (Figure 6-12 and Figure 6-13). The Trinity Group sediments form the underlying Trinity portion of the aquifer while the Fredericksburg and Lower Washita Group sediments form the overlying Edwards portion of the aquifer. The Edwards-Trinity (Plateau) Aquifer sediments rest unconformably on top of an uneven erosional surface of folded and faulted Paleozoic to Triassic-age sediments (Anaya, 2004).

The aquifer is mostly under water table or unconfined conditions, although the Trinity unit of the aquifer may be semi-confined locally where relatively impermeable sediments of the overlying basal member of the Edwards Group exists (Ashworth and Hopkins, 1995). The base of the aquifer slopes generally to the south and southeast. Most of the rocks that underlie the Edwards-Trinity (Plateau) Aquifer are much less permeable than the aquifer and function as a barrier to groundwater flow. Locally, the underlying rocks are permeable and are hydraulically connected to the Edwards-Trinity (Plateau) Aquifer, thus extending the thickness of the flow system.

Except for areas of significant karst-induced permeability, the average hydraulic conductivity of the Edwards-Trinity (Plateau) Aquifer sediments is about 10 feet per day (Barker and Ardis, 1996). Wells commonly yield from 50 to 200 gallons per minute. Well yields can vary greatly depending on the amount of development of secondary permeability in the limestone; yields from jointed and cavernous limestone can be as much as 3,000 gallons per minute.

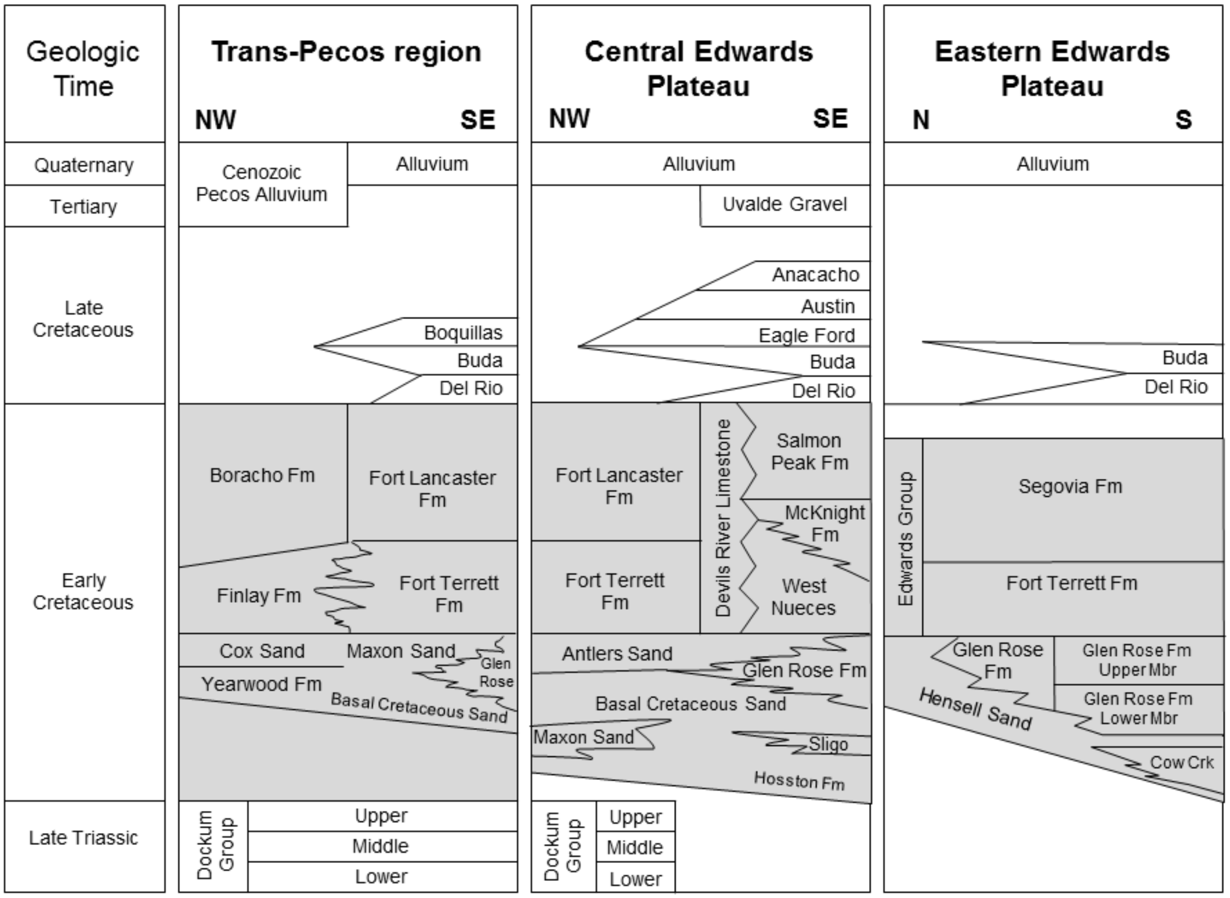


Figure 6-12. Stratigraphic chart of the Edwards Plateau region.

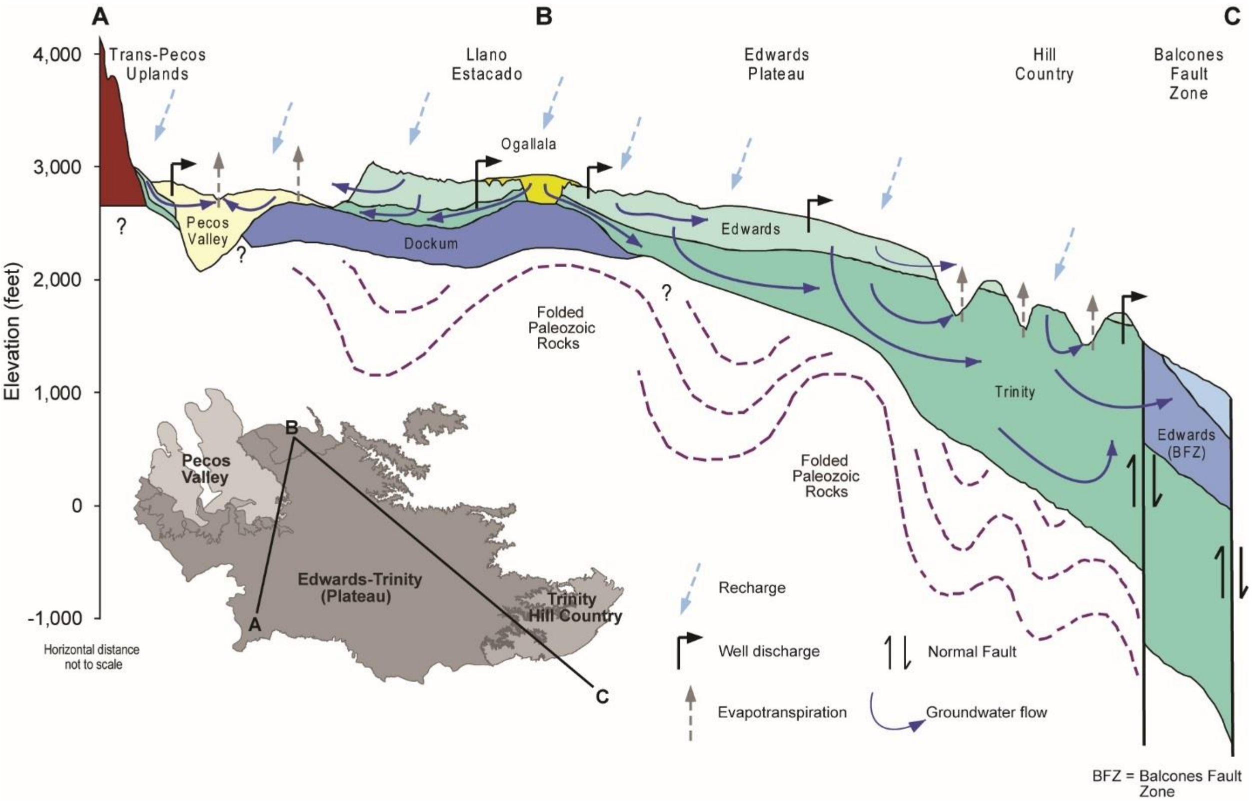


Figure 6-13. **Conceptual model of the Edwards-Trinity (Plateau) and Pecos Valley aquifers and the Hill Country part of the Trinity Aquifer (modified from Anaya and Jones, 2004, 2009).**

Flows to surface waters and other aquifers

Natural discharge from the Edwards-Trinity (Plateau) Aquifer to surface water occurs mostly from springs along the margins of the aquifer where the water table intersects the ground surface. Springs also discharge groundwater along the eastern flanks of the Trans-Pecos Mountains; the lower Pecos River canyons in Del Rio are the largest of these springs. As water levels have declined in the western portion of the aquifer due to increased irrigation pumping, springflows in those areas have also declined. In addition, many small springs that once flowed throughout the plateau have ceased flowing as a consequence of native grasslands being replaced by woody vegetation that consumes large amounts of potential recharge and allows more rainfall to run off before it is able to recharge the aquifer (Anaya, 2004).

Phreatophytic plants along major stream valleys, such as salt cedar on the Pecos River, discharge groundwater naturally as evapotranspiration. Most of the intermittent streams high on the plateau lose their flow to the underlying aquifer. The lower reaches of major streams along the northern, eastern, and southern margins of the plateau usually become gaining stream reaches when their stream channel elevation falls below the base of the Edwards unit. Table 6-8 summarizes groundwater flow from the Edwards-Trinity (Plateau) Aquifer to surface-water bodies. Table 6-9 shows the amount of springflow that contributes to baseflow.

The Edwards-Trinity (Plateau) Aquifer is hydraulically connected to four major aquifers: 1) Pecos Valley, 2) Ogallala, 3) Trinity, and 4) Edwards (Balcones Fault Zone). The aquifer is also hydraulically connected to several minor aquifers: 1) Dockum, 2) Capitan Reef Complex, 3) Rustler, 4) Hickory, 5) Ellenburger-San Saba, 6) Lipan, and, to a very small degree, 7) Marble Falls. Table 6-10 shows flow between the Edwards-Trinity (Plateau) and other aquifers.

Table 6-8. Summary of groundwater flow from the Edwards-Trinity (Plateau) Aquifer to surface water, by county.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Andrews	10	0	0
Bandera	209	33.5	12.1
Blanco	19	2	0.6
Brewster	1,513	19.9	12.5
Coke	288	1.2	0.5
Concho	370	2.6	1
Crane	34	0.1	0.1
Crockett	2,792	68.6	38.3
Culberson	323	2.3	0.8
Ector	504	2	1.4
Edwards	2,124	159.6	62.7
Gillespie	567	48.6	23.3
Glasscock	685	3.5	2.3
Howard	82	0.3	0.1
Irion	900	18	9.2
Jeff Davis	240	0.9	0.5
Kendall	90	10.3	3.6
Kerr	833	118.3	56.5
Kimble	1,236	80.9	35
Kinney	350	15.1	5
Martin	7	0	0
Mason	158	7.2	3

Table 6-8 (continued). Summary of groundwater flow from the Edwards-Trinity (Plateau) Aquifer to surface water, by county.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
McCulloch	277	4.9	1.5
Menard	891	29.6	12.2
Midland	406	2.1	0.9
Mitchell	1	0	0
Nolan	498	3	0.9
Pecos	3,408	52.7	54.2
Reagan	1,175	11.3	7.1
Real	687	91.2	32.8
Reeves	319	0.7	0.9
Schleicher	1,308	45.1	19.8
Sterling	623	2.6	1.5
Sutton	1,457	63.8	27.4
Taylor	189	1.6	0.3
Terrell	2,345	51	36.9
Tom Green	621	11.1	4.8
Upton	1,119	7.6	5.5
Uvalde	313	37.8	13.5
Val Verde	2,923	119.3	62.3
Winkler	21	0.1	0.1
Total	**31,915**	**1,130**	**551**

Table 6-9. Summary of springflow from the Edwards-Trinity (Plateau) Aquifer to surface water.

County	Sum of average annual springflow (cubic feet per second)	Sum of median annual springflow (cubic feet per second)	Spring names
Reagan	22.4	28	Comanche Springs at Ft Stockton, TX

Note: These values are included in the total baseflow values presented in Table 6-8.

Table 6-10. Model estimates of inter-aquifer flows between the Edwards-Trinity (Plateau) Aquifer and other major and minor aquifers.

Flow from	Flow to	Total flow (acre-feet per year)
Edwards-Trinity (Plateau) Aquifer	Dockum Aquifer	2,948
Edwards-Trinity (Plateau) Aquifer	Edwards (Balcones Fault Zone) Aquifer	25,626
Edwards-Trinity (Plateau) Aquifer	Ellenburger-San Saba Aquifer	929
Edwards-Trinity (Plateau) Aquifer	Hickory Aquifer	43
Edwards-Trinity (Plateau) Aquifer	Marble Falls Aquifer	7
Edwards-Trinity (Plateau) Aquifer	Ogallala Aquifer	7,341
Edwards-Trinity (Plateau) Aquifer	Pecos Valley Aquifer	45,966
Edwards-Trinity (Plateau) Aquifer	Trinity Aquifer	21,848
Edwards-Trinity (Plateau) Aquifer & other formations	Lipan Aquifer	7,507
Dockum Aquifer	Edwards-Trinity (Plateau) Aquifer	37,509
Lipan Aquifer	Edwards-Trinity (Plateau) Aquifer & Other Formations	7,506
Ogallala Aquifer	Edwards-Trinity (Plateau) Aquifer	3,014
Pecos Valley Aquifer	Edwards-Trinity (Plateau) Aquifer	647
Trinity Aquifer	Edwards-Trinity (Plateau) Aquifer	20,546

Water quantity

Total storage in the aquifer is estimated to be more than 45 million acre-feet. Recoverable storage is estimated to be between 25 and 75 percent of the total, about 11.3 million to 34.1 million acre-feet (Table 6-11). Water levels have remained rather stable because recharge has generally kept pace with the relatively low volume of water pumped from the aquifer. There are several areas in the northern and western plateau where water levels have declined as a result of increased pumping, including the agricultural district along the Reagan-Glasscock county boundary, and areas of concentrated oil production in Midland County. Figure 6-14 shows changes in water levels in the Edwards-Trinity (Plateau) Aquifer from 1995 to 2015.

Table 6-11. Total estimated recoverable storage in the Edwards-Trinity (Plateau) Aquifer, by groundwater management area, in acre-feet.

Groundwater management area	Total storage	25 percent of storage	75 percent of storage
2	142,000	35,500	106,500
3	390,300	97,575	292,725
4	3,780,000	945,000	2,835,000
7	38,821,000	9,705,250	29,115,750
9	2,358,000	589,500	1,768,500
Total	**45,491,300**	**11,372,825**	**34,118,475**

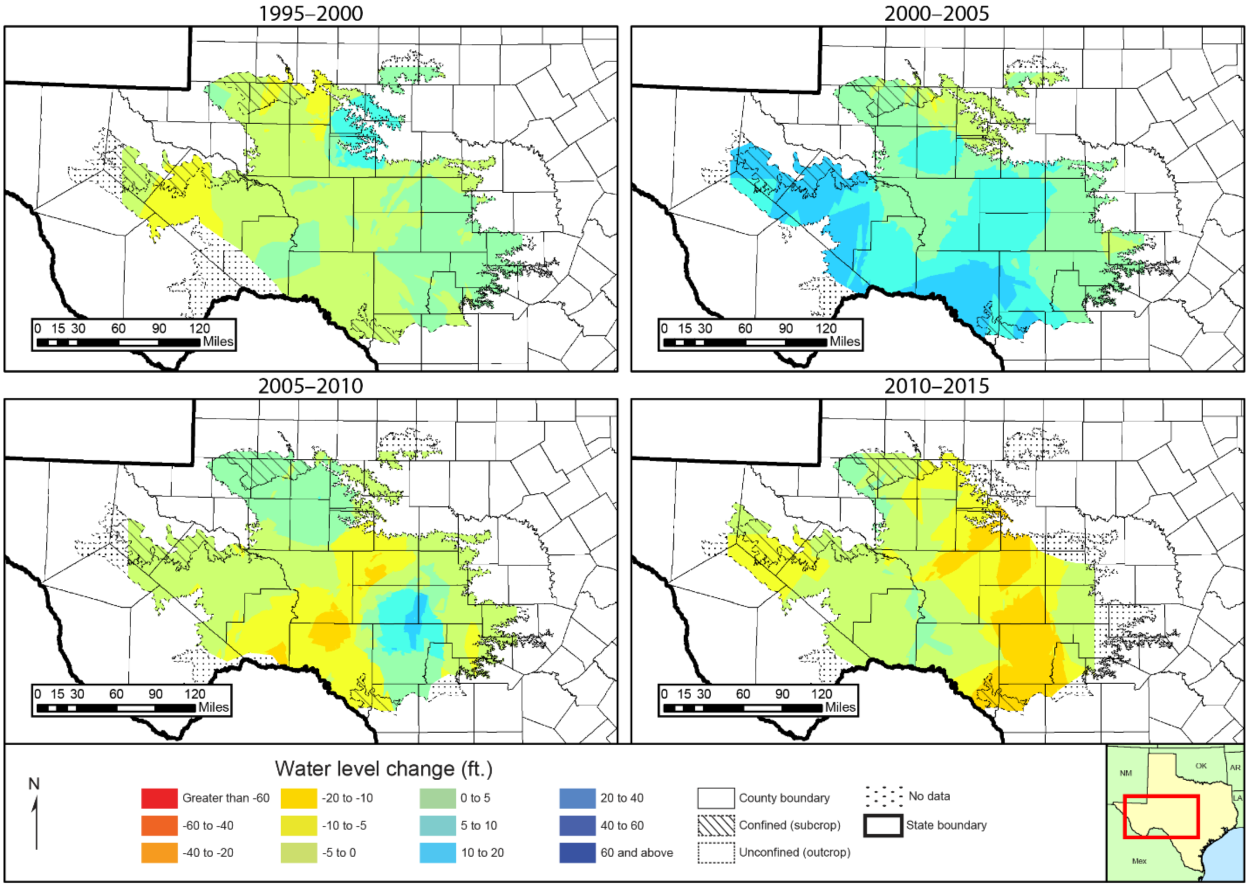


Figure 6-14. Water-level changes in the Edwards-Trinity (Plateau) Aquifer, 1995 to 2015.

Water quality

The water in the Edwards-Trinity (Plateau) Aquifer is generally a hard, calcium bicarbonate type and typically has total dissolved solids concentrations ranging from 400 to 1,000 milligrams per liter (Figure 6-15). Water quality in the unconfined portion of the aquifer is generally fresh, with only small, localized areas of slightly saline groundwater. Water typically increases in salinity to the west within the Trinity Group and in the confined portion of the aquifer where the groundwater is generally slightly to moderately saline.

Radionuclides are present in excess of drinking water standards in about 20 percent of the samples from the northwestern portion of the aquifer. Nitrate is present in excess of primary drinking water standards in a smaller number of samples. Groundwater exceeds secondary drinking water standards for total dissolved solids and sulfate in nearly 30 percent of samples, with less frequent exceedances for chloride, fluoride, iron, and manganese (Reedy and others, 2011).

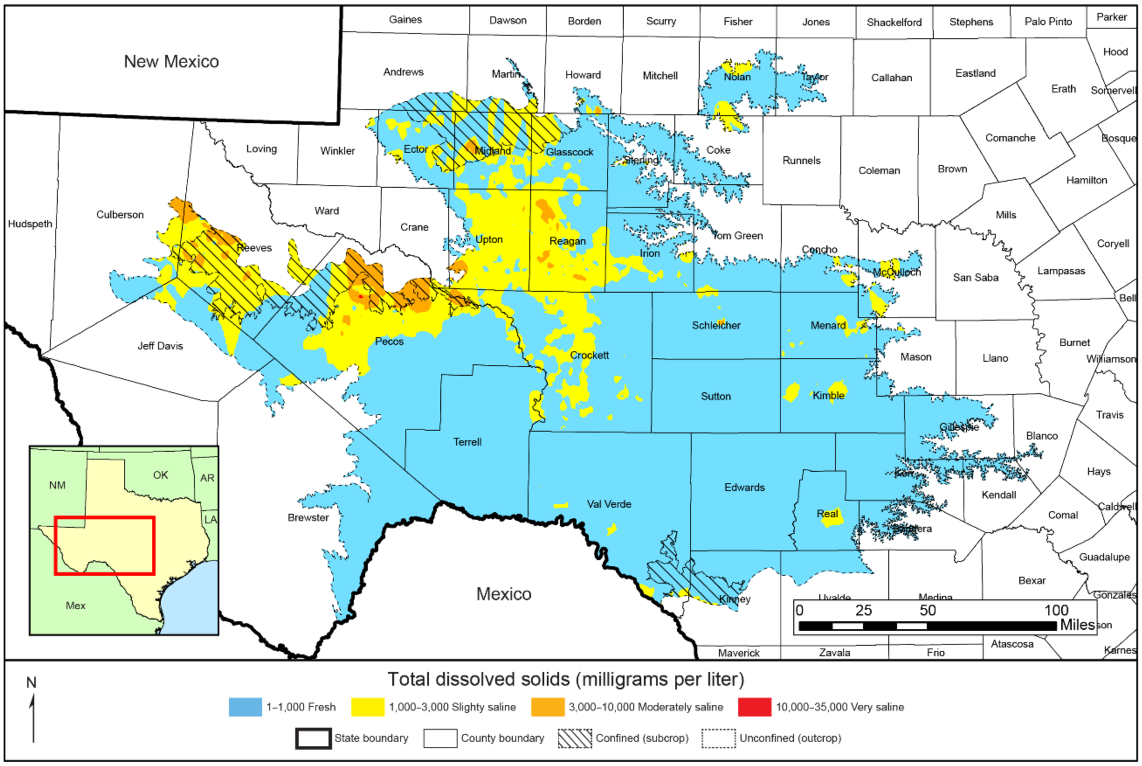


Figure 6-15. **Total dissolved solids in the Edwards-Trinity (Plateau) Aquifer.**

6.4 Gulf Coast Aquifer

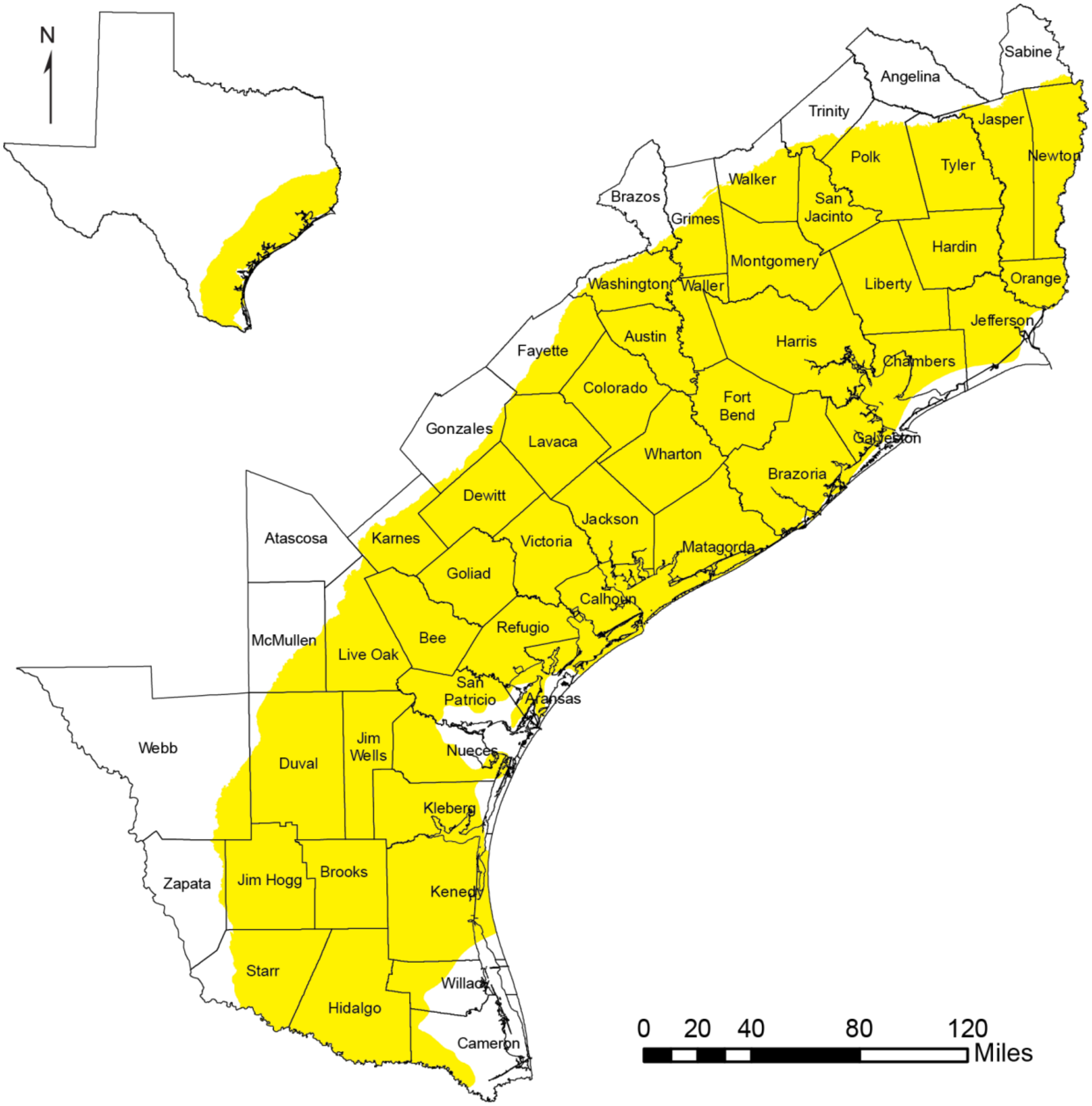


Figure 6-16. Extent of the Gulf Coast Aquifer.

Aquifer characteristics

- Aquifer type: confined and unconfined
- Area of aquifer: 41,970 square miles
- Proportion of aquifer with groundwater conservation districts: 81 percent
- Number of counties containing the aquifer: 56

Geology and hydrogeology

The Gulf Coast Aquifer is a major aquifer parallel to the Gulf of Mexico coastline from the Louisiana border to the Mexico border (Figure 6-16). It consists of several aquifers, including the Jasper, Evangeline, and Chicot aquifers, which are composed of discontinuous sand, silt, clay, and gravel beds of Miocene to Holocene age (Figure 6-17). The Oligocene Catahoula tuff forms a leaky confining layer at the base of the aquifer, and the Burkeville confining unit separates the Jasper Aquifer from the Evangeline Aquifer. All of the sedimentary units thicken toward the Gulf of Mexico. Growth faults, associated with loading on unconsolidated sediments, occur in several bands paralleling the coastline. Shallow salt domes locally intrude into the Gulf Coast Aquifer in the Houston embayment, with tops ranging from 0 to 2,000 feet deep (Hamlin, 2006).

Freshwater saturated thickness in the Gulf Coast Aquifer averages about 1,000 feet. The maximum total sand thickness ranges from 700 feet in the south to 1,300 feet in the north. The hydraulic conductivity of the aquifer also increases from 1 foot per day in the south to 7 feet per day in the northeast (Chowdhury and others, 2004). The transmissivity of the aquifer ranges from less than 1,000 feet squared per day in the southern portion to over 14,000 feet squared per day in the northeast.

Groundwater in the Gulf Coast Aquifer is typically unconfined or semi-confined. The groundwater availability model for the central Gulf Coast Aquifer determined calibrated specific storage values of 8×10^{-6} to 1×10^{-5} and specific yield values of 0.05 to 0.005. These specific yield values are low compared to typical specific yields of sedimentary materials in unconfined aquifers, which range from 0.14 to 0.38 (Freeze and Cherry, 1979). The lower specific yields in the Chicot, Evangeline, and Jasper aquifers reflect the numerous interbedded silt/clay lenses that locally confine groundwater in these aquifers (Chowdhury and others, 2004).

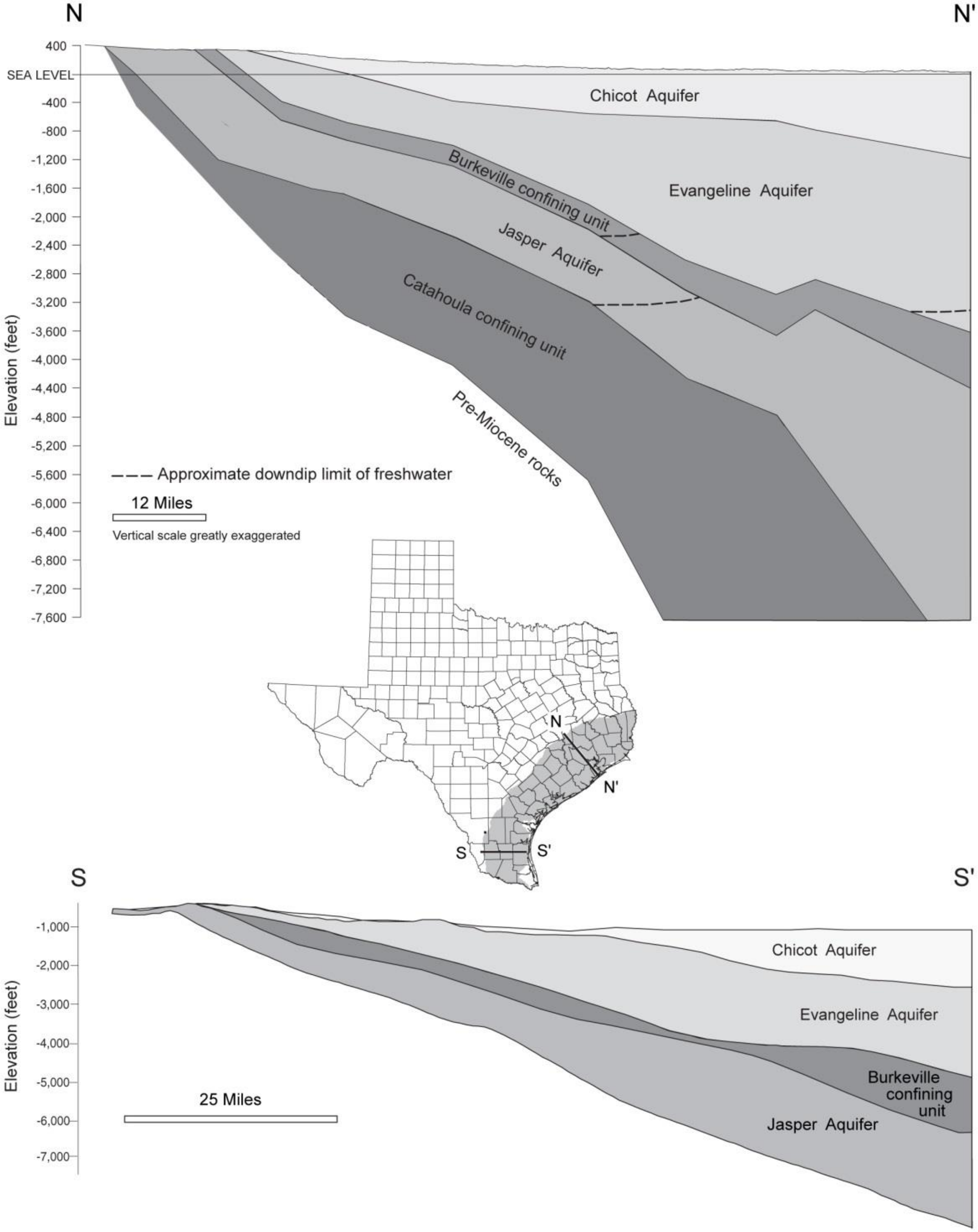


Figure 6-17. **Cross-sections across the Gulf Coast Aquifer (modified from Baker, 1979, 1986; Chowdhury and Mace, 2003; Kasmarek and Robinson, 2004).**

Flows to surface water and other aquifers

Of the total annual flow of approximately 620,000 acre-feet, about 84 percent discharges into the streams, and 16 percent discharges into the Gulf of Mexico (Chowdhury and others, 2004). Table 6-12 summarizes groundwater flow from the Gulf Coast Aquifer to surface water.

Cross-formational flow between the different aquifers and the confining units is generally upward. About 1,400 acre-feet per year flows from the Jasper Aquifer to the Burkeville confining unit, about 6,000 acre-feet per year flows from the Burkeville confining unit to the overlying Evangeline Aquifer, and about 20,000 acre-feet per year flows from the Evangeline to the overlying Chicot Aquifer. This suggests existence of a strong regional upward flow in the central Gulf Coast Aquifer system.

The down-dip boundary for the regional Gulf Coast Aquifer System should allow groundwater discharge across a large area of the ocean bottom. Two of three Gulf Coast Aquifer System groundwater availability models extend the regional flow system to about 10 miles past the coastline. These two models allow the exchange of flow between the ocean and the groundwater in the Chicot Aquifer. One of the Gulf Coast Aquifer System groundwater availability models has the down-dip boundary of the regional flow system terminate at the coast line. The groundwater flow paths inferred from the geochemical data suggest that near the coast the groundwater flow is predominantly horizontal or slightly downward. These inferred groundwater flow directions are in agreement with the general findings of Glover (1959). For the scenario of no pumping along the coastline, Glover (1959) shows that groundwater discharge should extend outward into the ocean. Glover’s analysis shows that the distance groundwater flows into the ocean is a function of flow rate in the aquifer, the permeability of the aquifer, and the density differences between the ocean water and groundwater.

Groundwater from the Gulf Coast Aquifer System flows into the Brazos River Alluvium Aquifer, but the relative magnitude of the inflows are unknown. Further data is required to quantify this flow and flow from the Brazos River Alluvium Aquifer into the Gulf Coast Aquifer.

Table 6-12. Summary of groundwater flow from the Gulf Coast Aquifer to surface water, by county.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Angelina	4	1.5	0.6
Aransas	193	9.9	1
Atascosa	0	0	0
Austin	592	57.2	9.6
Bee	880	20.7	3.6
Brazoria	1,405	461.6	190.4
Brazos	4	0.4	0.1
Brooks	943	8.3	1.4
Calhoun	424	42	4.3
Cameron	258	4.8	0.7
Chambers	527	186.9	57.3
Colorado	974	63.9	13.7
DeWitt	910	85	25.7
Duval	1,714	13.3	2.6
Fayette	560	29.5	6.9
Fort Bend	689	111.5	28.2
Galveston	289	94.8	26.1
Goliad	860	43.9	10.6
Gonzales	136	9.8	2.1
Grimes	407	38.7	5.4
Hardin	897	334.5	119.9
Harris	1,747	377.8	86.1
Hidalgo	1,584	20.6	3.2
Jackson	851	78.6	10.7
Jasper	933	348.3	144.4
Jefferson	739	212.4	45.8
Jim Hogg	1,126	10	1.9
Jim Wells	869	9	1.8
Karnes	566	25.4	8.2
Kenedy	1,323	16.7	2.4
Kleberg	786	16.2	2
Lavaca	970	72	13.3
Liberty	1,175	440.6	182

Table 6-12 (continued). Summary of groundwater flow from the Gulf Coast Aquifer to surface water, by county.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Live Oak	966	19.9	3.8
Matagorda	1,122	202.5	56.1
McMullen	290	3.5	0.8
Montgomery	1,077	178.3	35.6
Newton	934	355.5	138.9
Nueces	622	15.8	1.9
Orange	346	89.5	16.7
Polk	974	251.8	71.1
Refugio	777	40.2	4.1
Sabine	27	13	6.1
San Jacinto	629	111.8	22.2
San Patricio	516	15.6	1.4
Starr	946	10.1	1.9
Trinity	91	14.4	2.6
Tyler	888	339.5	144
Victoria	889	78	11.1
Walker	552	75.3	9.6
Waller	420	48.2	10.5
Washington	493	42.1	7.1
Webb	292	2	0.4
Wharton	1,094	112	23.3
Willacy	271	3.6	0.6
Zapata	54	0.4	0.1
Total	**39,605**	**5,269**	**1,582**

Water quantity

Total groundwater storage in the Gulf Coast Aquifer is estimated to be 5.1 billion acre-feet. Recoverable groundwater storage is estimated to be between 25 and 75 percent of the total, about 1.2 billion to 3.8 billion acre-feet (Table 6-13). The large volume of groundwater pumped from the Gulf Coast Aquifer in the Houston area has caused land subsidence, but groundwater management strategies have been implemented to prevent further subsidence. In response, groundwater levels have rebounded in areas using these strategies, rising by more than 200 feet in some locations between 2000 and 2015. At the same time, groundwater extraction has shifted to areas north and west of Houston, where groundwater levels declined more than 100 feet between 2000 and 2015. Figure 6-18 shows water level changes in the Gulf Coast Aquifer from 1995 to 2015.

Table 6-13. Total estimated recoverable storage in the Gulf Coast Aquifer, by groundwater management area, in acre-feet.

Groundwater management area	Total storage	25 percent of storage	75 percent of storage
11	1,447,000	361,750	1,085,250
12	450,000	112,500	337,500
13	2,460,000	615,000	1,845,000
14	2,776,000,000	694,000,000	2,082,000,000
15	368,800,000	92,200,000	276,600,000
16	2,032,350,000	508,087,500	1,524,262,500
Total	**5,181,507,000**	**1,295,376,750**	**3,886,130,250**

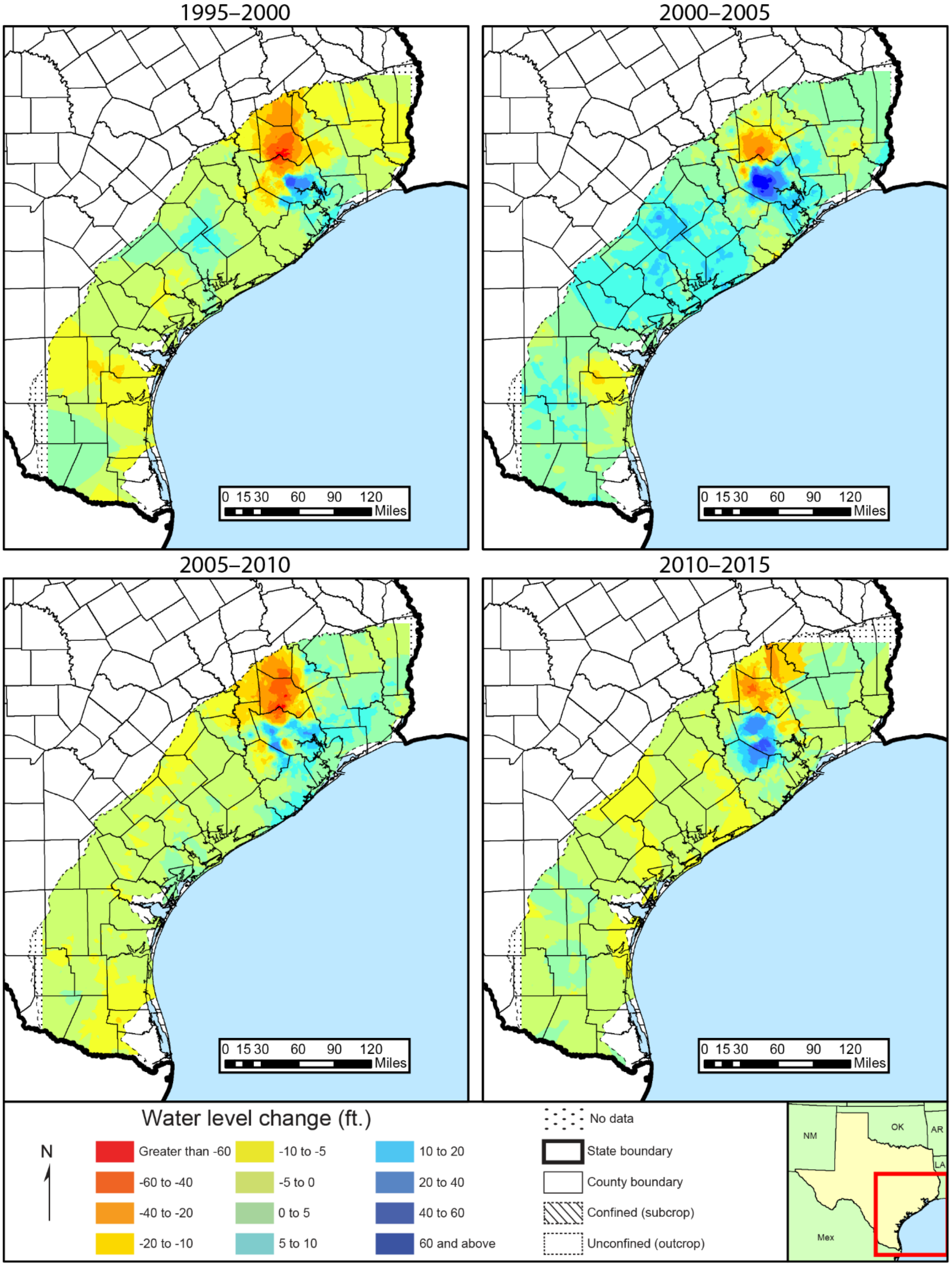


Figure 6-18. **Water-level changes in the Gulf Coast Aquifer, from 1995 to 2015.**

Water quality

Water quality varies with depth and locality. It is generally good in the central and northeastern parts of the aquifer, where total dissolved solids concentrations are less than 500 milligrams per liter but is more saline to the south, where total dissolved solids are typically 1,000 to more than 10,000 milligrams per liter and where the productivity of the aquifer decreases (Figure 6-19). Areas of increased salinity along the central and eastern Gulf Coast may be associated with saltwater intrusion in response to groundwater pumping or to brine migration in response to oil field operations and natural flows from salt domes intruding into the aquifer.

The extent of the aquifer along the Gulf Coast is generally defined by the down-dip limit of freshwater; the sedimentary units making up the aquifer continue below the Gulf of Mexico but become increasingly saline as a result of interaction with seawater, increasing groundwater residence time, and mixing with oil-field brines.

Arsenic and radionuclides are found in excess of primary drinking water standards in many wells in the Gulf Coast Aquifer, predominantly in the southern region. These contaminants are associated with the tuffaceous sands of the Catahoula Formation at the base of the aquifer and can be mobilized into the Gulf Coast Aquifer along leaky fault zones and around salt domes (Adams and Smith, 1980; Reedy and others, 2011). Chloride, iron, manganese, and total dissolved solids exceed secondary drinking water standards in up to 28 percent of wells sampled; iron and manganese exceedances are mostly in the northern portion of the aquifer, while chloride and total dissolved solids exceedances mostly occur in the southern part of the aquifer (Reedy and others, 2011).

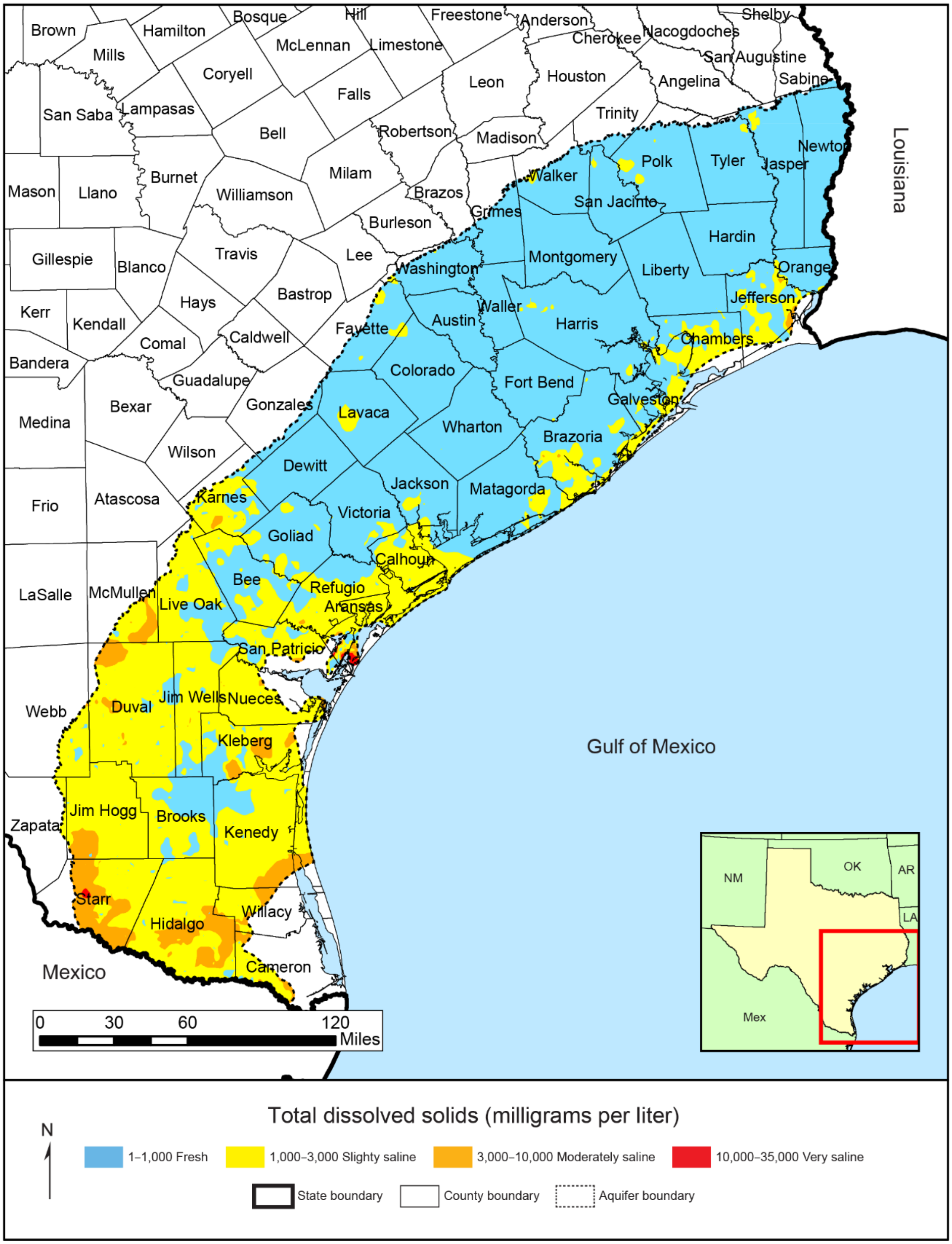


Figure 6-19. **Total dissolved solids in the Gulf Coast Aquifer.**

6.5 Hueco-Mesilla Bolsons Aquifer

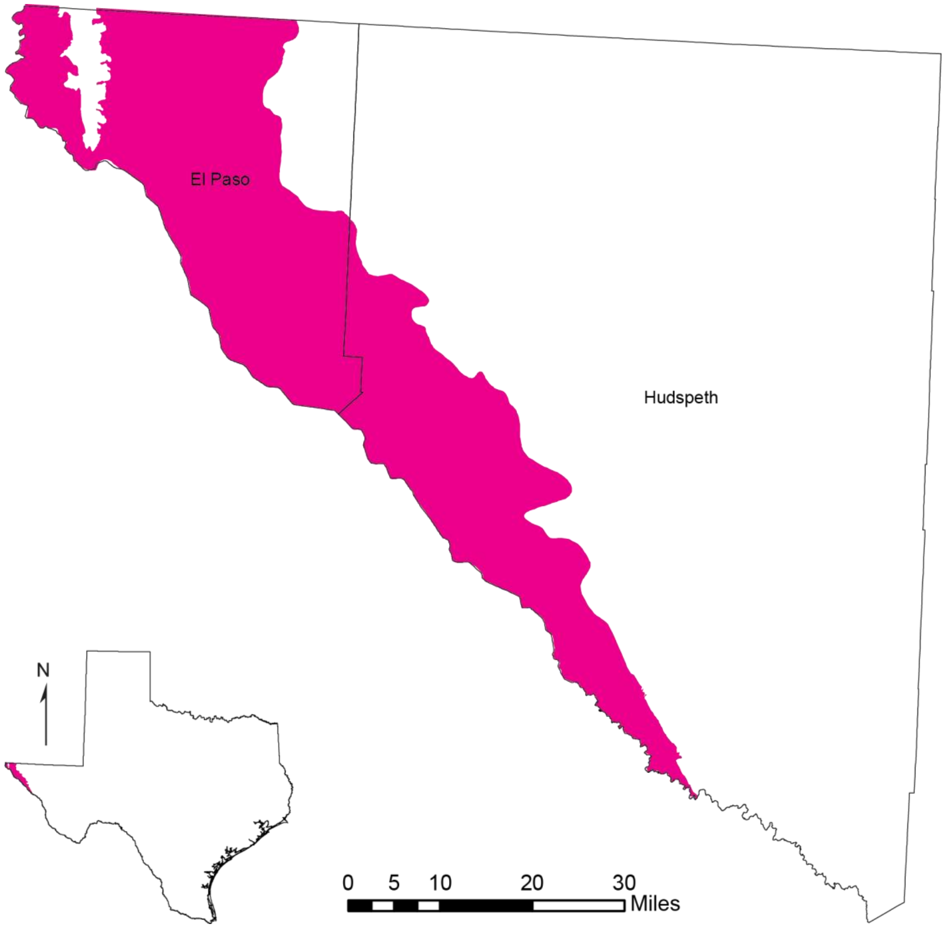


Figure 6-20. Extent of the Hueco-Mesilla Bolsons Aquifer.

Aquifer characteristics

- Aquifer type: unconfined
- Area of aquifer: 1,376 square miles
- Proportion of aquifer with groundwater conservation districts: 0 percent
- Number of counties containing the aquifer: 2

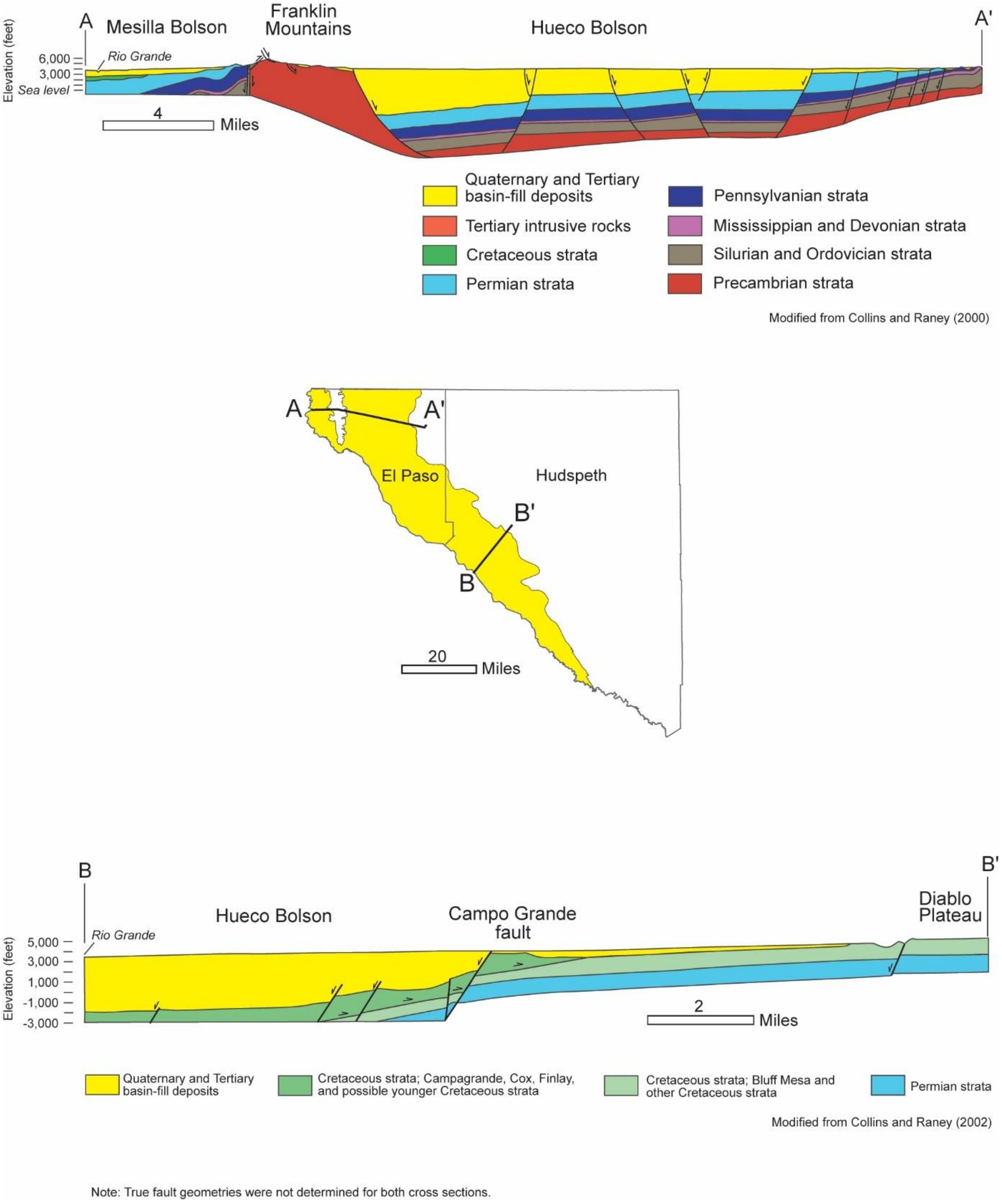
Geology and hydrogeology

The Hueco-Mesilla Bolsons Aquifer is a major aquifer located in El Paso and Hudspeth counties in far west Texas (Figure 6-20). The Hueco Bolson is considered the southern portion of the Tularosa-Hueco Basin. The northern portion of the aquifer, the Tularosa Basin, lies entirely in the state of New Mexico (Heywood and Yager, 2003). The Hueco and Mesilla Bolsons also extend under the Rio Grande into Mexico.

The Hueco Bolson is a fault-bounded structural depression associated with the Rio Grande Rift. Low-permeability igneous rocks of Precambrian age and sedimentary rocks of Paleozoic and Mesozoic age surround and underlie the Hueco Bolson (Figure 6-21) and are typically modeled as no-flow boundaries.

The aquifer is composed of unconsolidated to poorly consolidated basin-fill consisting of silt, sand, gravel, and clay in two basins, or bolsons: the Hueco Bolson, which has a maximum thickness of 9,000 feet, and the Mesilla Bolson, which has a maximum thickness of 2,000 feet. The average horizontal hydraulic conductivity ranges from 22 feet per day in alluvial fan sediments to 3.0 feet per day in lacustrine deposits (Heywood and Yager, 2003). The specific yield is estimated to be 0.18 (Heywood and Yager, 2003).

Prior to development, the Rio Grande was a gaining river in the El Paso area. Groundwater recharged in the northern parts of the aquifer and moved southward to discharge into the Rio Grande in the vicinity of downtown El Paso and Cuidad Juarez (Brehehoeft and others, 2004). That flow regime has been reversed by pumping. Today about half of the recharge to the aquifer comes from the Rio Grande, with the balance representing flow from the Tularosa Basin in New Mexico into the Hueco Bolson. Infiltration through permeable mountain-front alluvial fans represents a much smaller volume of recharge (Heywood and Yager, 2003).



Modified from Collins and Raney (2000)

Modified from Collins and Raney (2002)

Note: True fault geometries were not determined for both cross sections.

Figure 6-21. **Cross-sections across the Hueco-Mesilla Bolsons Aquifer (modified from Collins and Raney, 2000, 2002).**

Flows to surface water and other aquifers

There is no net discharge from the Hueco-Mesilla Bolsons Aquifer to surface water because of pumping in El Paso and Ciudad Juarez and associated water-level declines; at this time the Rio Grande is a losing stream and recharges the aquifer. Table 6-14 shows flow from the Hueco-Mesilla Bolsons Aquifer to surface water, as estimated from stream baseflow and surface runoff measurements.

Although the Hueco and Mesilla Bolsons share similar geology, very little water travels between them. Groundwater underflow from the Mesilla Basin to the Hueco Bolson may occur adjacent to the Rio Grande, but the underflow is estimated to be less than 80 acre-feet per year (Heywood and Yager, 2003). Groundwater levels in the Tularosa Basin (McLean, 1970) indicate a regional flow component to the south into the Hueco Bolson.

The area of the Hueco-Mesilla Bolsons Aquifer does not connect with any other major or minor aquifer in Texas, and there are no flows between the Hueco-Mesilla Bolsons Aquifer and any other major or minor aquifers in Texas.

Table 6-14. Summary of groundwater flow from the Hueco-Mesilla Bolsons Aquifer to surface water, by county.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
El Paso	786	3.2	2.8
Hudspeth	535	3.5	3.3
Total	**1,321**	**7**	**6**

Water quantity

El Paso Water Utilities has estimated the total volume of fresh groundwater in the Texas portion of the Hueco Bolson at 9 million acre-feet (Brehehoeft, Ford, Harden, Mace, and Rumbaugh, 2004). Water levels declined several hundred feet up to the late 1980s due primarily to municipal pumping in the Hueco Bolson. Since that time, however, observation wells indicate that water levels have stabilized. Figure 6-22 shows water-level changes in the Hueco-Mesilla Bolsons Aquifer from 1995 to 2015.

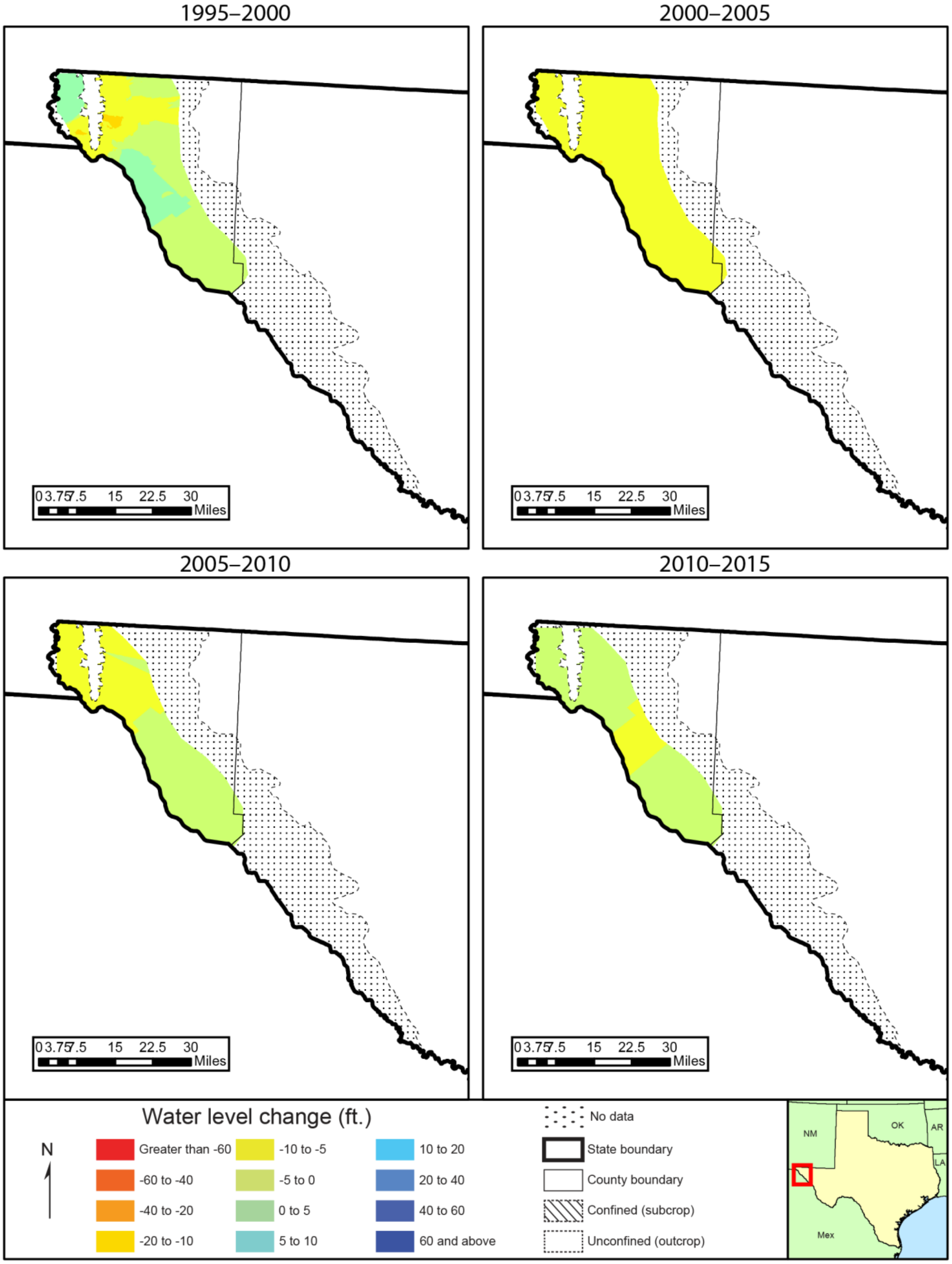


Figure 6-22. Water-level changes in the Hueco-Mesilla Bolsons Aquifer, 1995 to 2015.

Water quality

Fresh groundwater stored in the aquifer system beneath El Paso and Ciudad Juarez is bordered by regions of brackish to saline groundwater. As water levels in the freshwater portions of the aquifer declined, intrusion of the surrounding brackish water degraded water quality. Figure 6-23 shows the distribution of total dissolved solids in the Hueco-Mesilla Bolsons Aquifer.

The upper portion of the Hueco Bolson contains fresh to slightly saline water, with total dissolved solids concentrations ranging from 1,000 to 3,000 milligrams per liter. The Mesilla Bolson also contains fresh to saline water, with total dissolved solids concentrations ranging from less than 1,000 to 10,000 or more milligrams per liter of total dissolved solids. Its salinity typically increases to the south and in the shallower parts of the aquifer. In both aquifers, water-level declines have contributed to brackish water intrusion and increased salinity.

Arsenic is present in portions of the Hueco Bolson at concentrations exceeding drinking water criteria, primarily in the eastern and southern portions of the Hueco Bolson. A total of 17 out of 31 groundwater samples collected by the TWDB for dissolved arsenic between 2000 and 2015 contain concentrations exceeding the maximum contaminant level of 10 micrograms per liter, with a maximum concentration of 60.1 micrograms per liter. Secondary water quality standards for chloride, fluoride, iron, manganese, sulfate, and total dissolved solids are also exceeded in some samples (Reedy and others, 2011).

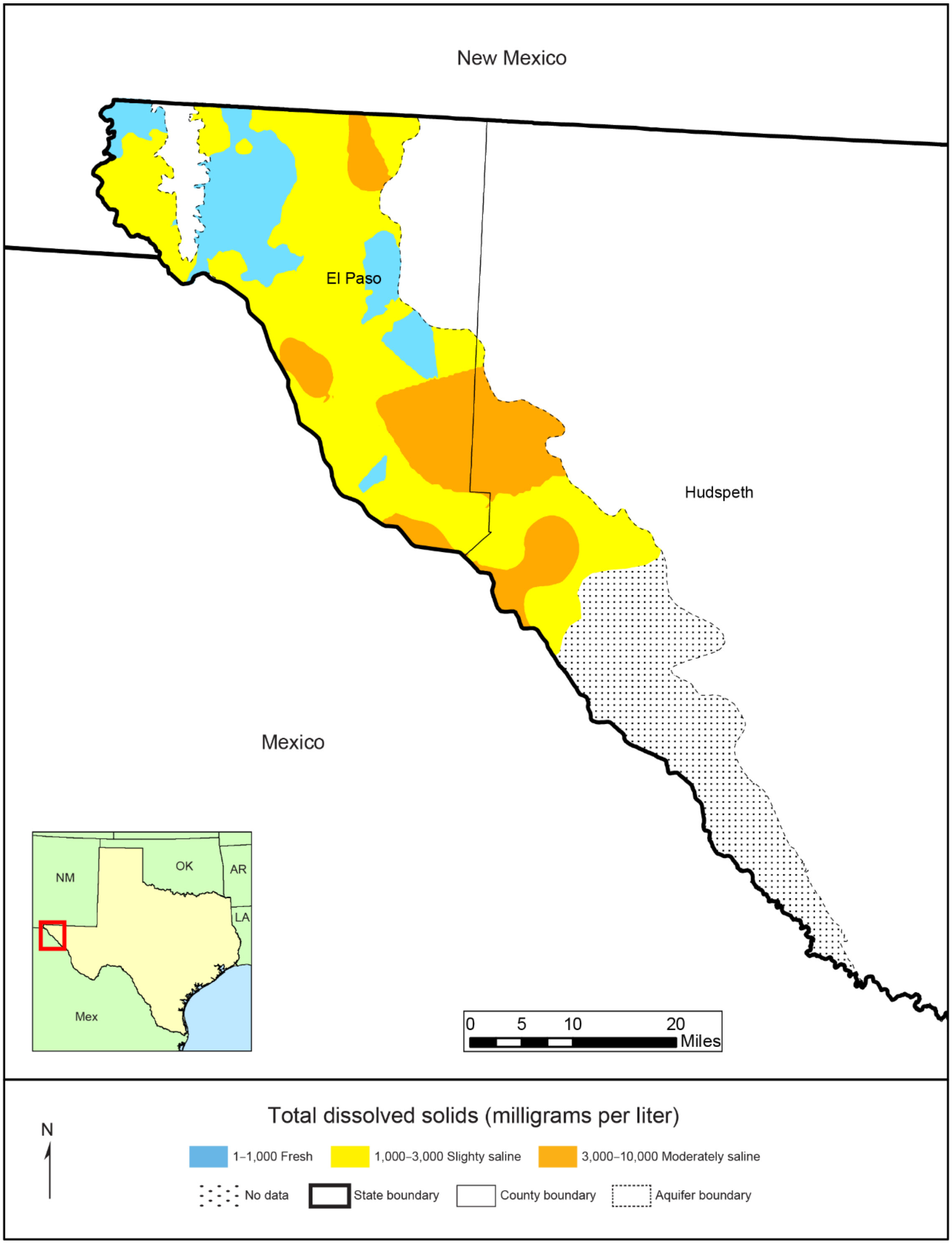


Figure 6-23. Total dissolved solids in the Hueco-Mesilla Bolsons Aquifer.

6.6 Ogallala Aquifer

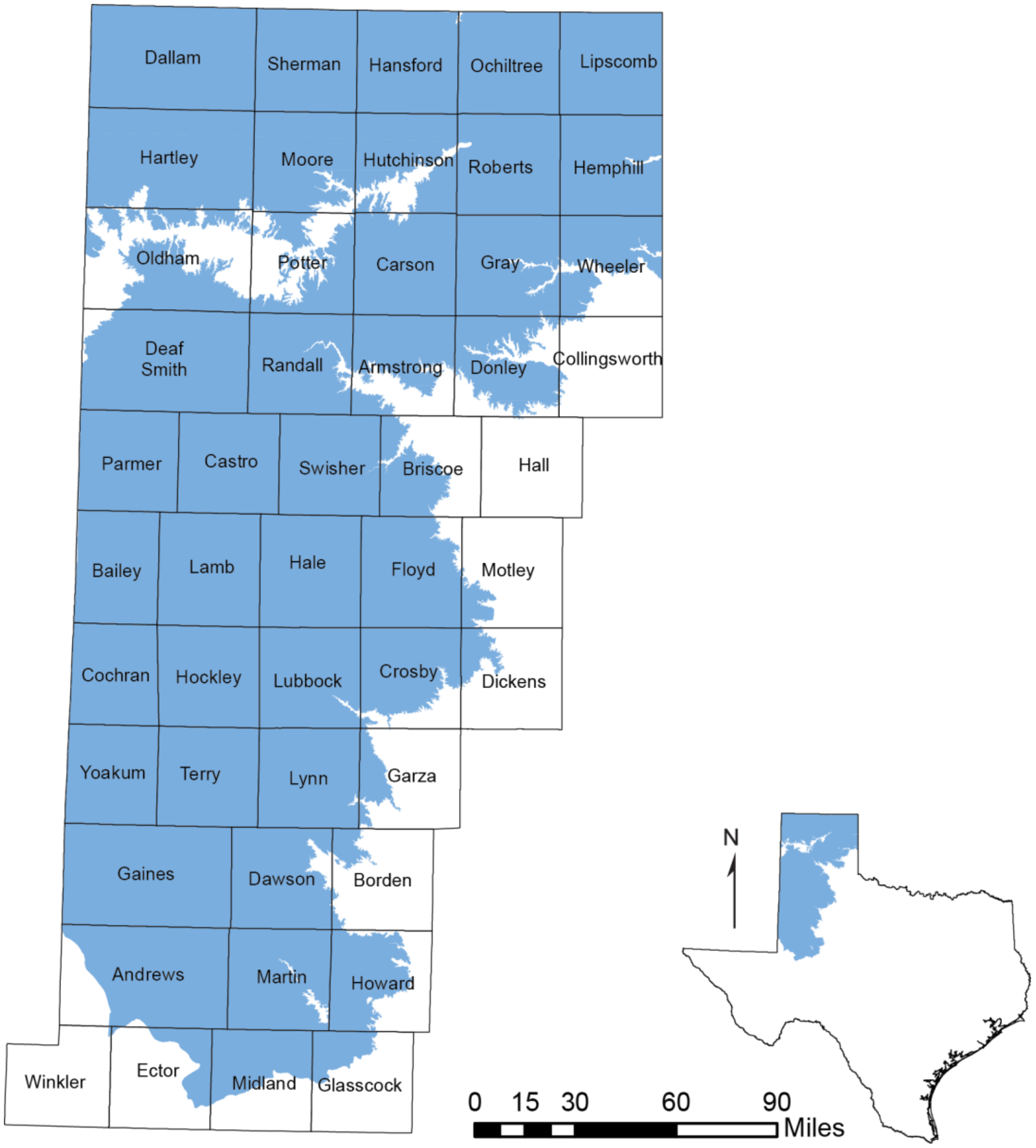


Figure 6-24. Extent of the Ogallala Aquifer in Texas.

Aquifer characteristics

- Aquifer type: unconfined
- Area of aquifer: 36,293 square miles
- Proportion of aquifer with groundwater conservation districts: 86 percent
- Number of counties containing the aquifer: 49

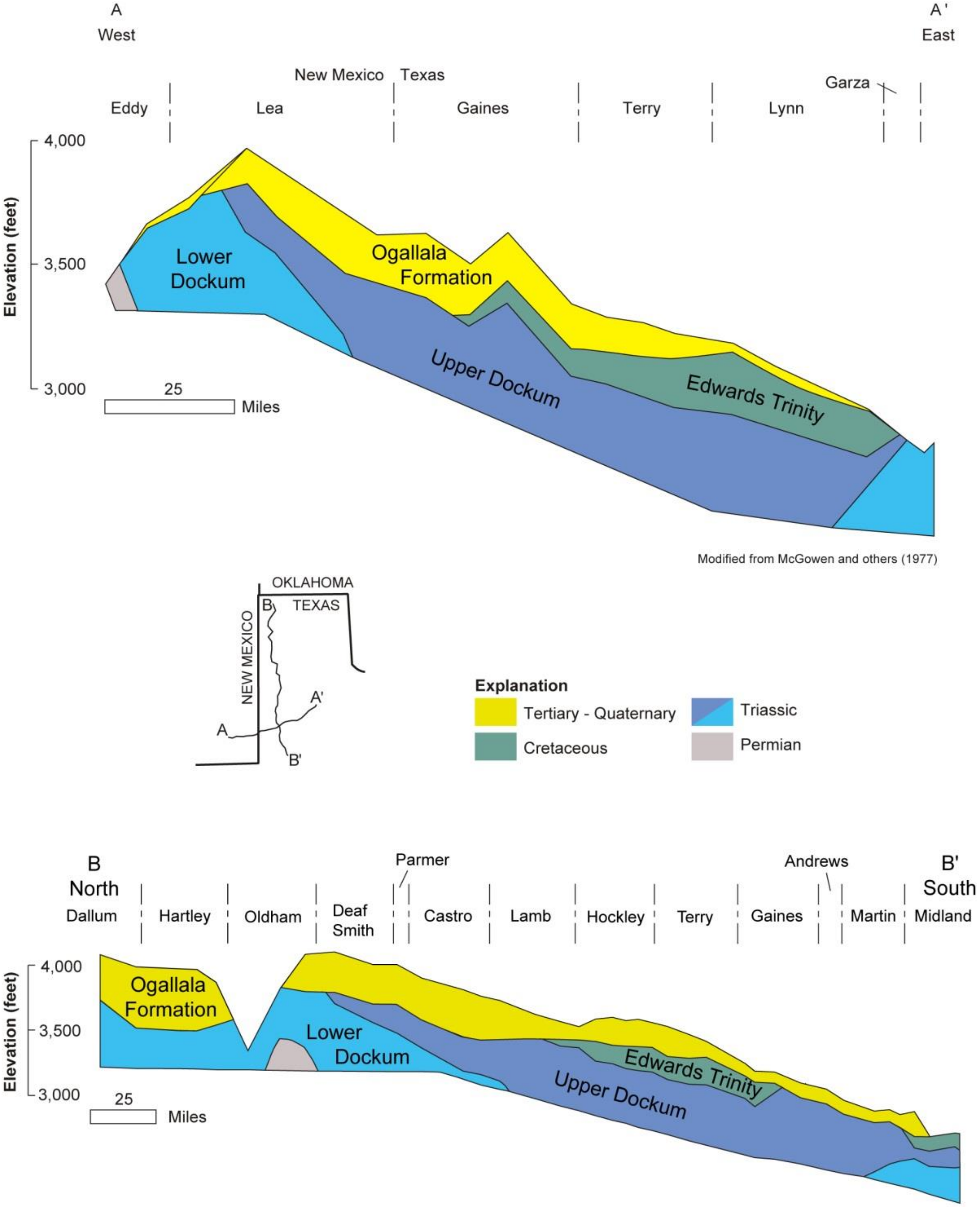
Geology and hydrogeology

The Ogallala Aquifer, an unconfined aquifer, is the largest aquifer in the United States and is a major aquifer of Texas, underlying much of the High Plains region (Figure 6-24). The aquifer consists of sand, gravel, clay, and silt and has a maximum thickness of 800 feet. Freshwater saturated thickness in the aquifer averages 95 feet but is significantly greater in several paleovalleys that were eroded into the Permian- to Cretaceous-aged surfaces before deposition of the Ogallala Formation.

The Ogallala Formation was deposited as alluvial outwash from the Rocky Mountains. The thickest and coarsest grained sediments are fluvial channel facies in alluvial fan lobes deposited in paleovalleys (Seni, 1980; Gustavson, 1996), where pebble- to boulder-size gravel lenses are common along the basal surface. Three major paleovalleys are located north of the Canadian River, and a smaller paleovalley stretches from near Clovis to southeast of Plainview. Most sediment in the preserved extent of the Ogallala Formation are sands and gravels that were deposited in braided stream channels (Seni, 1980). The Ogallala Formation becomes finer-grained with increased distance from the mountains. The Ogallala Formation is overlain by the Blackwater Draw Formation, which forms a layer of Quaternary eolian fine sand, silt, clay, and caliche that covers the Ogallala Formation except along breaks and draws.

The hydraulic conductivity of the Southern Ogallala Aquifer ranges from 0.01 to 2,600 feet per day with a mean of about 6.8 feet per day (Blandford, 2003). The geometric mean of hydraulic conductivity in the Northern Ogallala Aquifer is about 14.8 feet per day with a standard deviation of 5 to 44 feet per day (Dutton, 2001). The specific yield of the Ogallala Aquifer ranges from 15 to 22 percent, with an average of 16 percent (Blandford, 2003).

Studies indicate that recharge represents a small fraction of current water usage. Most recently, Deeds and Hamlin (2015) developed detailed maps of present-day recharge, dividing the Ogallala into two regions. Recharge in the southern region has been affected by agricultural development and ranges from 0.007 to over 3 inches per year, with the most recharge in areas where irrigated crops are raised on relatively permeable soils. In the northern region, relatively clayey soils limit agricultural influence on recharge, and the pre-development distribution of recharge remains in place, with rates ranging from 0.1 to 0.8 inches per year.



Modified from McGowen and others (1977)

Figure 6-25. Geologic cross-sections showing the relationship of the Ogallala Formation to underlying strata (modified from McGowen and others, 1977).

Flows to surface water and other aquifers

Baseflow from springs or aquifer discharge has diminished due to the large volume of pumping for irrigation from the Ogallala Aquifer, resulting in low to no flow in streams that originally depended on aquifer discharge (Deeds and Hamlin, 2015). Table 6-15 summarizes groundwater flow from the Ogallala Aquifer to surface water.

The Ogallala Aquifer is in hydraulic communication with the underlying Cretaceous Edwards-Trinity (Plateau) Aquifer in the south, the Rita Blanca Aquifer in the northwest, and the Triassic Dockum Aquifer in the central region. Table 6-16 shows groundwater availability model estimates of total flow and average annual flow between the Ogallala Aquifer and other aquifers.

Table 6-15. Summary of groundwater flow from the Ogallala Aquifer to surface water by county.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Andrews	1,215	4.3	3.1
Armstrong	620	1.6	1.1
Bailey	820	2.4	1.4
Borden	105	0.4	0.3
Briscoe	404	1.6	1.2
Carson	912	3.4	2.5
Castro	900	1.1	0.1
Cochran	775	2	1.4
Collingsworth	16	0.1	0
Crosby	696	5.3	5
Dallam	1,505	13.1	5.1
Dawson	846	2.9	1.8
Deaf Smith	1,439	3.1	0.8
Dickens	123	1	0.6
Donley	619	4.2	1.9
Ector	207	0.8	0.6
Floyd	924	7.7	6.6
Gaines	1,501	4.4	3.8
Garza	158	0.9	0.8
Glasscock	199	1	0.3

Table 6-15. Summary of groundwater flow from the Ogallala Aquifer to surface water by county.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Gray	903	8.5	5.4
Hale	1,005	2.4	2.2
Hall	1	0	0
Hansford	917	3	1.7
Hartley	1,424	3.7	2.5
Hemphill	902	11	7
Hockley	910	1.1	1
Howard	548	1.8	0.7
Hutchinson	717	2.6	1.5
Lamb	1,018	2	1.5
Lipscomb	932	8.5	4.4
Lubbock	893	2.7	2.6
Lynn	889	3.8	4.4
Martin	884	3.6	1.7
Midland	496	2.2	1.2
Moore	842	2.7	0.9
Motley	100	1.2	0.9
Ochiltree	914	6.7	2.9
Oldham	733	3.9	1.6
Parmer	879	2	0.8
Potter	497	1.6	0.8
Randall	889	1.5	0.7
Roberts	917	6	4.5
Sherman	921	4.1	1.6
Swisher	900	1.7	0.9
Terry	890	1.9	1.3
Wheeler	581	13	8
Winkler	3	0	0
Yoakum	799	2.3	1.8
Total	**36,288**	**167**	**103**

Table 6-16. Model estimates of inter-aquifer flows between the Ogallala Aquifer and other major and minor aquifers.

Flow from	Flow to	Total flow (acre-feet per year)
Ogallala Aquifer	Dockum Aquifer	27,497
Ogallala Aquifer	Edwards-Trinity (High Plains) Aquifer	13,812
Ogallala Aquifer	Edwards-Trinity (Plateau) Aquifer	3,014
Ogallala Aquifer	Pecos Valley Aquifer	220
Ogallala Aquifer	Rita Blanca Aquifer	1,670
Dockum Aquifer	Ogallala Aquifer	2,241
Edwards-Trinity (High Plains) Aquifer	Ogallala Aquifer	5,544
Edwards-Trinity (Plateau) Aquifer	Ogallala Aquifer	7,341

Water quantity

Total storage in the Ogallala Aquifer is estimated to be more than 380 million acre feet. Recoverable storage is estimated to be between 25 and 75 percent of the total, about 95.1 million to 285.4 million acre-feet (Table 6-17). Throughout much of the Ogallala Aquifer, groundwater withdrawals exceed the amount of recharge, and water levels have declined over time. Although water-level declines in excess of 300 feet have occurred in several areas over the last 50 to 60 years, the rate of decline has slowed, and water levels have risen in a few areas. Figure 6-26 shows changes in water levels in the Ogallala Aquifer.

Table 6-17. Total estimated recoverable storage in the Ogallala Aquifer, by groundwater management area, in acre-feet.

Groundwater management area	Total storage	25 percent of storage	75 percent of storage
1	232,700,000	58,175,000	174,525,000
2	139,210,000	34,802,500	104,407,500
3	9,600	2,400	7,200
6	2,285,000	571,250	1,713,750
7	6,340,000	1,585,000	4,755,000
Total	**380,544,600**	**95,136,150**	**285,408,450**

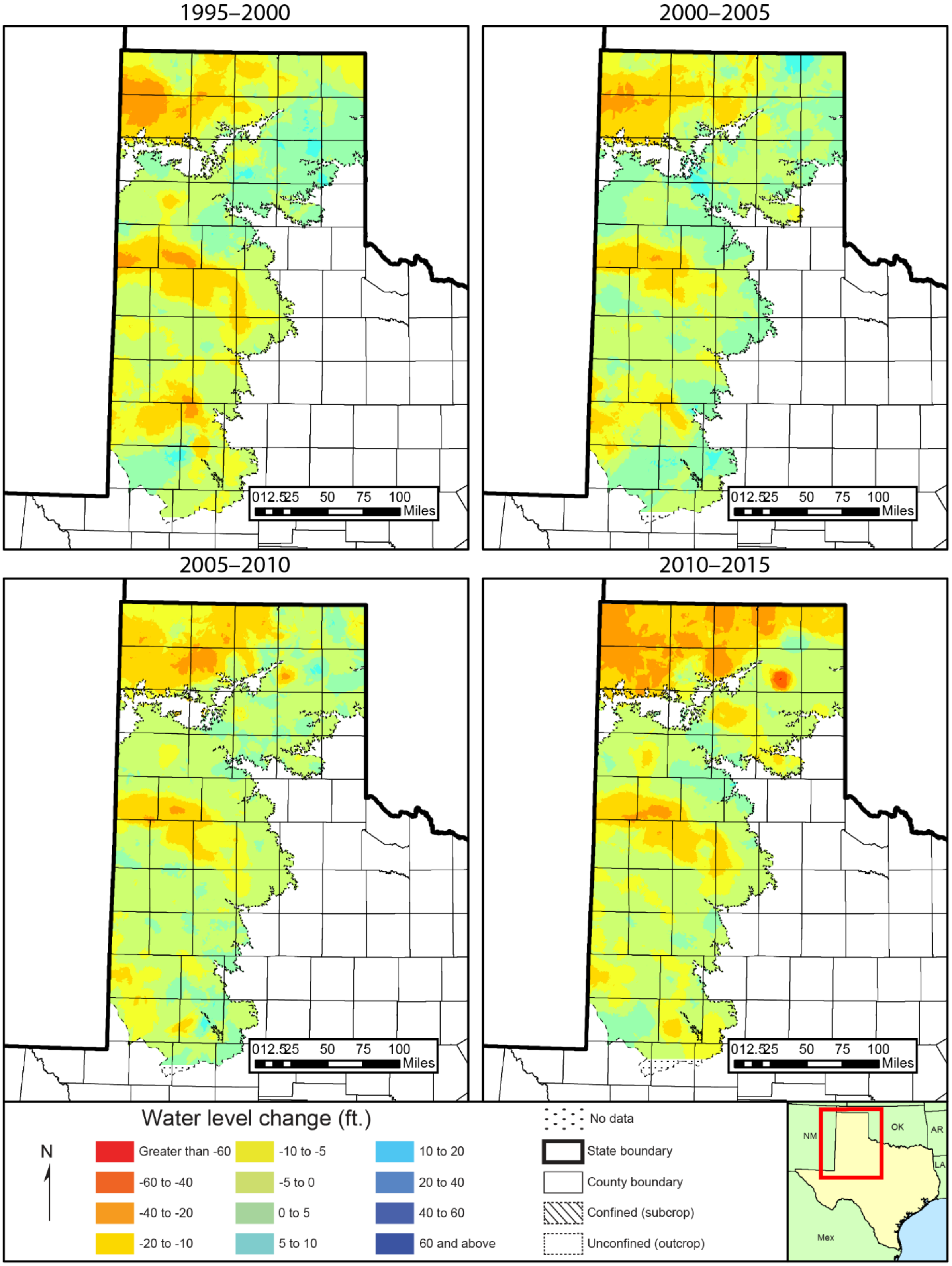


Figure 6-26. **Water-level changes in the Ogallala Aquifer, 1995 to 2015.**

Water quality

Water to the north of the Canadian River is generally fresh, with total dissolved solids concentrations typically less than 400 milligrams per liter. However, water quality diminishes to the south, where large areas contain total dissolved solids concentrations greater than 1,000 milligrams per liter (Figure 6-27). Increased salinity may be associated with evaporative concentration of groundwater in saline playa lakes in the southern portion of the aquifer, upflow of more saline groundwater from the underlying Dockum Aquifer, and other sources (Reedy and others, 2011).

Arsenic, fluoride, nitrate, radionuclides, and selenium levels have been known to be in excess of primary drinking water standards, primarily in the southern portion of the aquifer. Volcanic ash leaching in the aquifer is likely the source of arsenic, fluoride, selenium, and radionuclides. Sources of nitrate may come from agricultural activity in the area (Reedy and others, 2011).

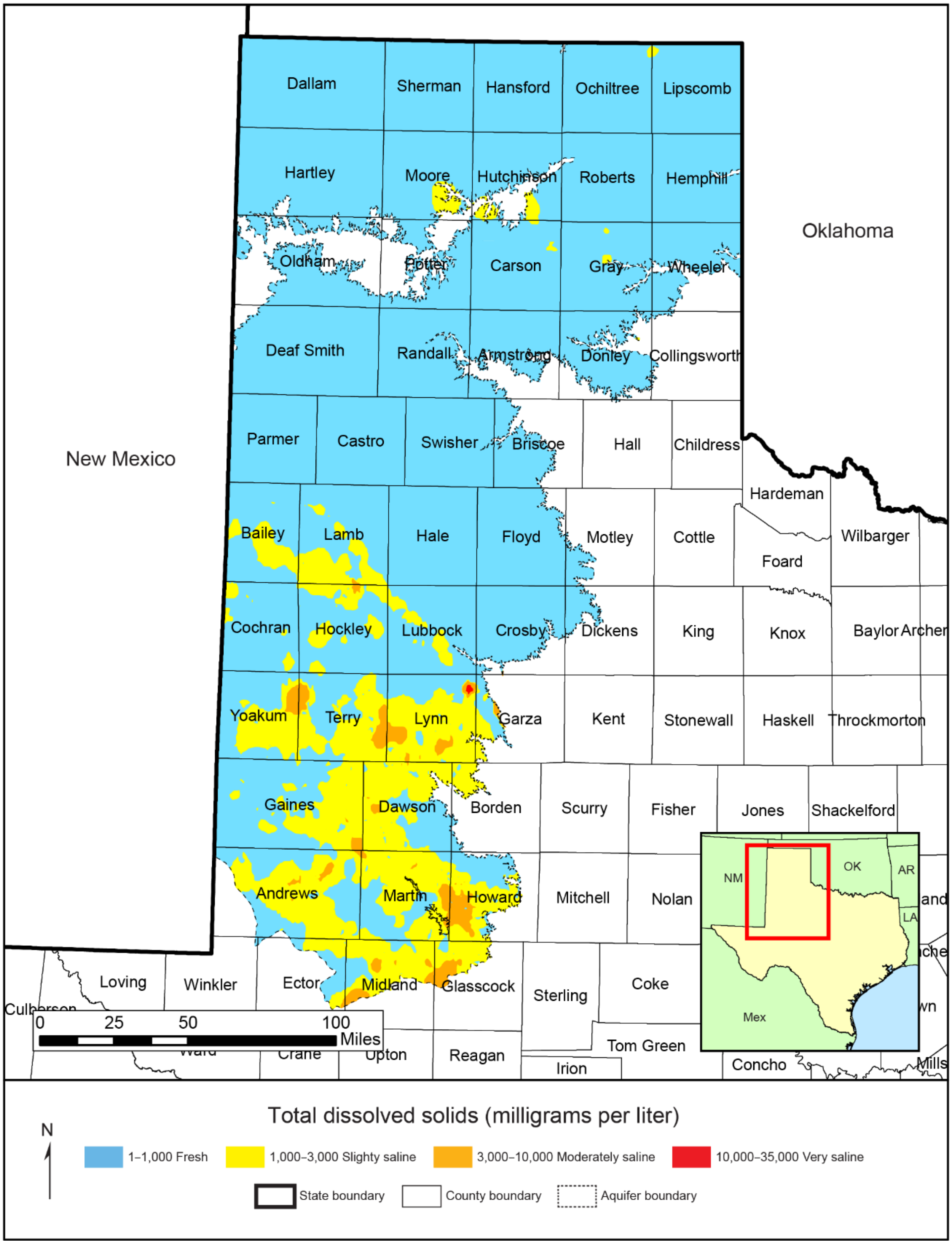


Figure 6-27. Total dissolved solids in the Ogallala Aquifer.

6.7 *Pecos Valley Aquifer*

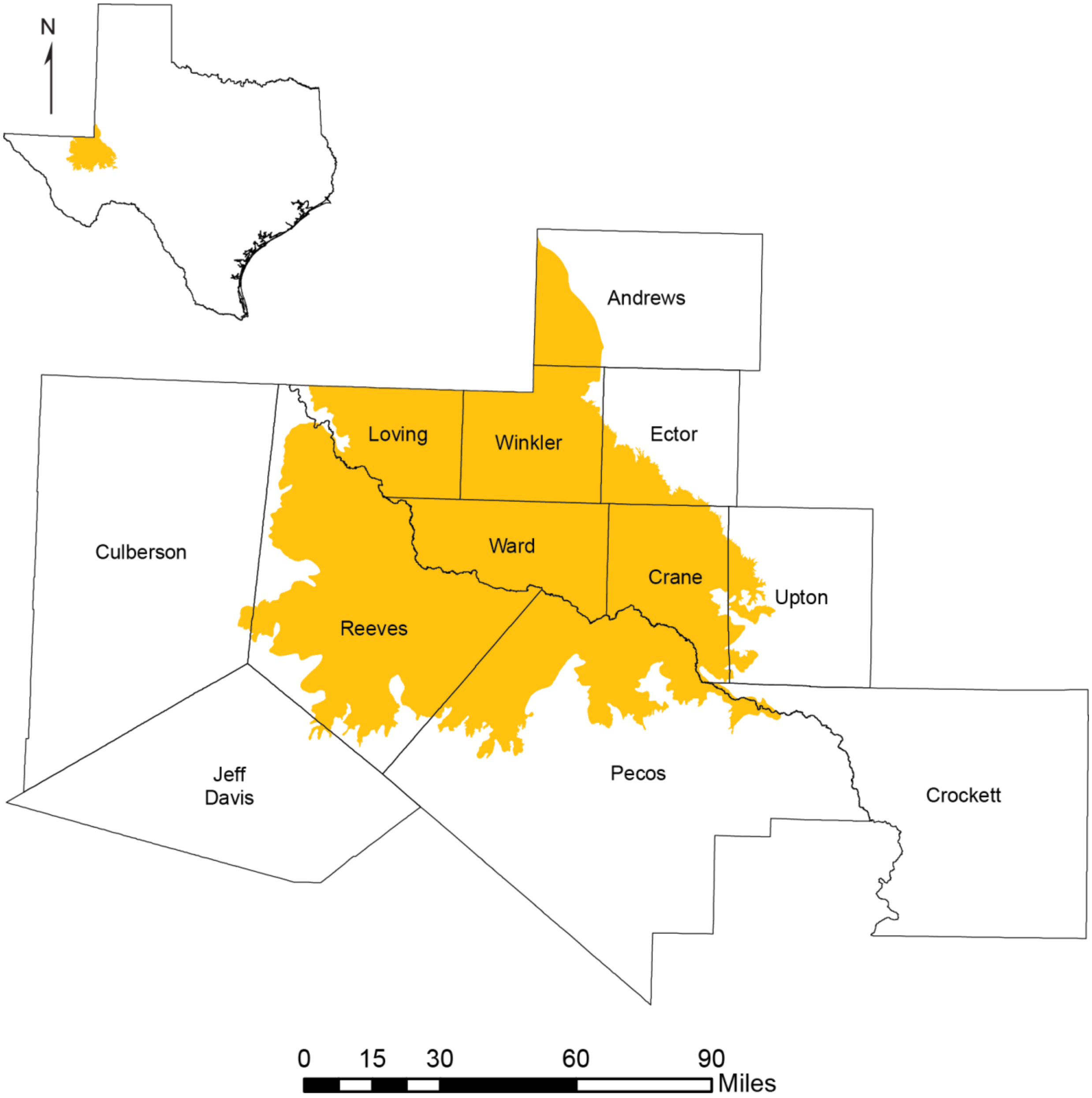


Figure 6-28. Extent of the Pecos Valley Aquifer.

Aquifer characteristics

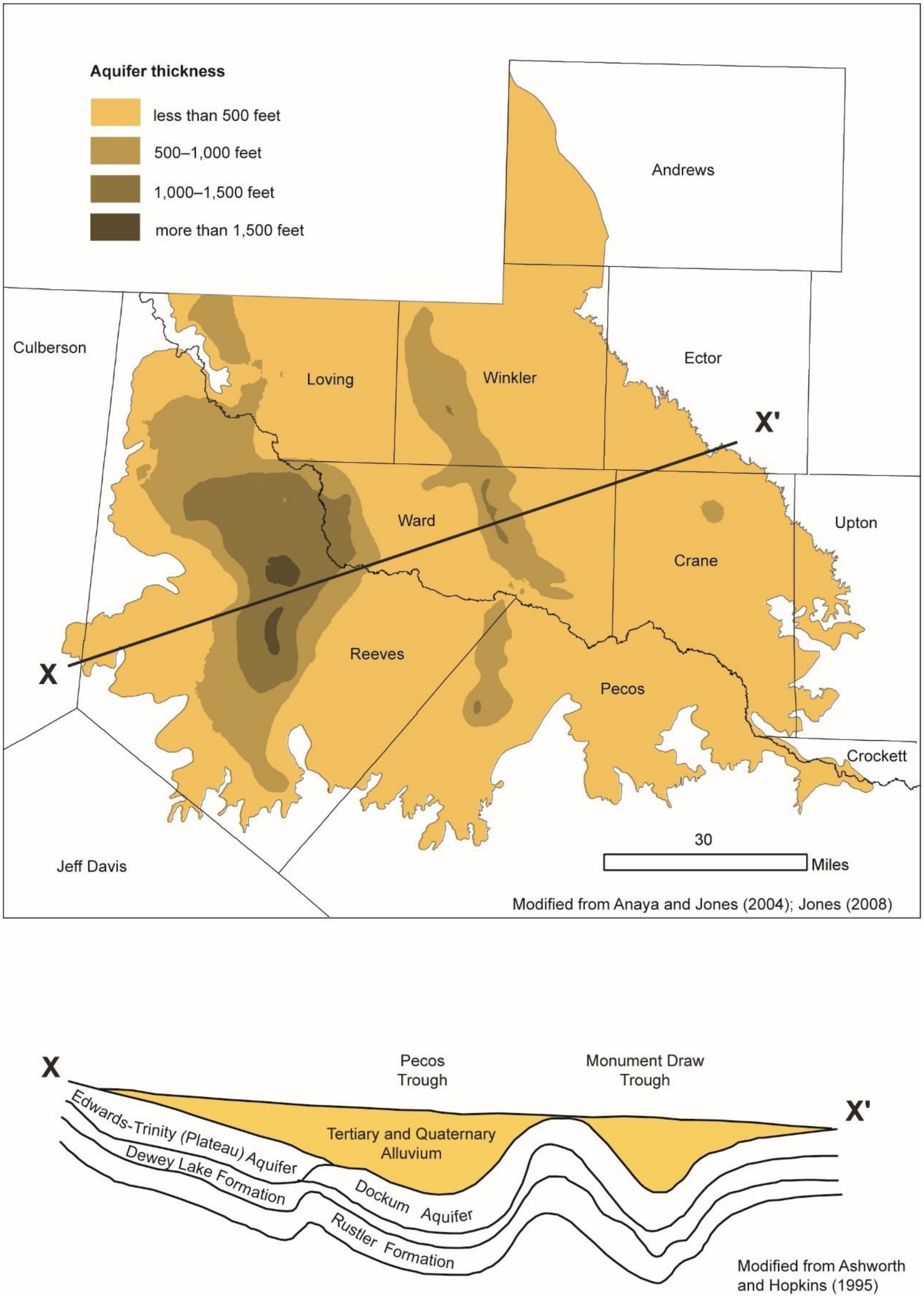
- Aquifer type: unconfined
- Area of aquifer: 6,829 square miles
- Proportion of aquifer with groundwater conservation districts: 47 percent
- Number of counties containing the aquifer: 12

Geology and hydrogeology

The Pecos Valley Aquifer is a major aquifer in west Texas. It consists of alluvial, lacustrine, and eolian deposits of Tertiary and Quaternary age deposited in the Pecos River Valley (Figure 6-28). Some of the valley fill deposits correlate with the Ogallala Formation (Hawley and others, 1976). These sediments fill several structural basins, the largest of which are the Pecos Trough in the west and Monument Draw Trough in the east (Figure 6-29). Thickness of the alluvial fill reaches 1,500 feet, and freshwater saturated thickness averages about 250 feet.

Groundwater in the Pecos Valley Aquifer is unconfined. The top of the aquifer is exposed at the ground surface over the entire extent of the aquifer. Recharge to the Pecos Valley Aquifer is estimated at about 89,800 acre-feet per year (Anaya and Jones, 2009). Recharge is generally higher south and west of the Pecos River. Return flows from Pecos River water applied for irrigation are estimated to be over 50 percent of the recharge to the Pecos Valley Aquifer (Ashworth, 1990). Induced recharge from the Pecos River also occurs in Pecos and Reeves counties, where irrigation pumping has drawn down the water table (Barker and Ardis, 1996).

The Pecos Valley Aquifer has a hydraulic conductivity ranging from 4 to 20 feet per day (Figure 6-30), a specific yield of 0.2, and specific storage of 0.0002, based on calibrated model results (Anaya and Jones, 2009).



Modified from Anaya and Jones (2004); Jones (2008)

Modified from Ashworth and Hopkins (1995)

Figure 6-29. **Generalized cross-sections across the Pecos Valley Aquifer (modified from Ashworth and Hopkins, 1995; Anaya and Jones, 2004; Jones, 2008).**

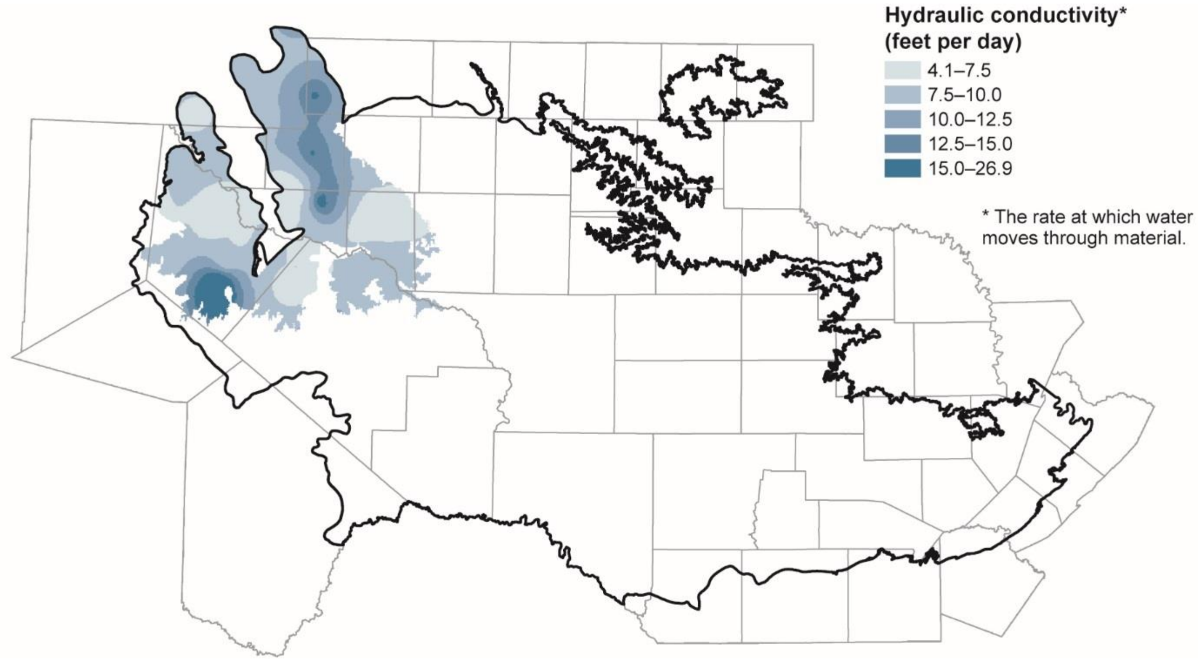


Figure 6-30. **Interpolated hydraulic conductivity for the Pecos Valley Aquifer (from Anaya and Jones, 2009).**

Flows to surface water and other aquifers

The Pecos Valley Aquifer discharges through evapotranspiration along the Pecos River where the water table is near the surface, as baseflow to the Pecos River, and as pumping from irrigation wells. Except for local cones of depression caused by intense pumping, groundwater flow in the Pecos Valley Aquifer is generally toward the Pecos River (Anaya and Jones, 2009). Table 6-18 summarizes groundwater flow from the Pecos Valley Aquifer to surface water. Table 6-19 shows the amount of springflow that makes up baseflow.

The Pecos Valley Aquifer is hydraulically connected to the underlying minor aquifers—the Dockum, Capitan Reef Complex, and Rustler aquifers. Groundwater flow between the Pecos Valley Aquifer and the minor aquifers is assumed to be insignificant based on geochemical data (Anaya and Jones, 2009). Table 6-20 shows groundwater availability model estimates of total flow and average annual flow between the Pecos Valley Aquifer and other major aquifers.

Table 6-18. Summary of groundwater flow from the Pecos Valley Aquifer to surface water, by county.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Andrews	276	0.8	0.8
Crane	747	2.4	2.2
Crockett	12	0.1	0.1
Culberson	14	0	0
Ector	192	0.6	0.6
Jeff Davis	7	12.1	11.7
Loving	635	1.9	1.8
Pecos	1,056	3	3.4
Reeves	2,116	39.6	37.6
Upton	120	0.4	0.4
Ward	836	2.2	2.3
Winkler	816	2.2	2.4
Total	**6,827**	**65**	**63**

Table 6-19. Summary of springflow from the Pecos Valley Aquifer to surface water.

County	Sum of average annual springflow (cubic feet per second)	Sum of median annual springflow (cubic feet per second)	Spring names
Jeff Davis	12.4	12	Phantom Lake Spring near Toyahvale, TX
Reeves	34.1	32	San Soloman Springs at Toyahvale, TX

Note that these values have been added to the total baseflow presented in Table 6-18

Table 6-20. Model estimates of inter-aquifer flows between the Pecos Valley Aquifer and other major aquifers.

Flow from	Flow to	Total flow (acre-feet per year)
Pecos Valley Aquifer	Edwards-Trinity (Plateau) Aquifer	647
Pecos Valley Aquifer	Ogallala Aquifer	0
Edwards-Trinity (Plateau) Aquifer	Pecos Valley Aquifer	45,966
Ogallala Aquifer	Pecos Valley Aquifer	220

Water quantity

Total storage in the Pecos Valley Aquifer is estimated to be more than 323 million acre-feet Recoverable storage is estimated to be between 80.9 million and 242.8 million acre-feet (Table 6-21). Localized water levels have rebounded in south central Reeves and northwest Pecos counties since the late 1970s as irrigation pumping has decreased. However, water levels continue to decline in central Ward County because of increased municipal and industrial pumping. Figure 6-31 shows water-level changes in the Pecos Valley Aquifer from 1995 to 2015.

Table 6-21. Total estimated recoverable storage in the Pecos Valley Aquifer, by groundwater management area, in acre-feet.

Groundwater management area	Total storage	25 percent of storage	75 percent of storage
2	2,000,000	500,000	1,500,000
3	309,000,000	77,250,000	231,750,000
4	1,490,000	372,500	1,117,500
7	11,370,000	2,842,500	8,527,500
Total	**323,860,000**	**80,965,000**	**242,895,000**

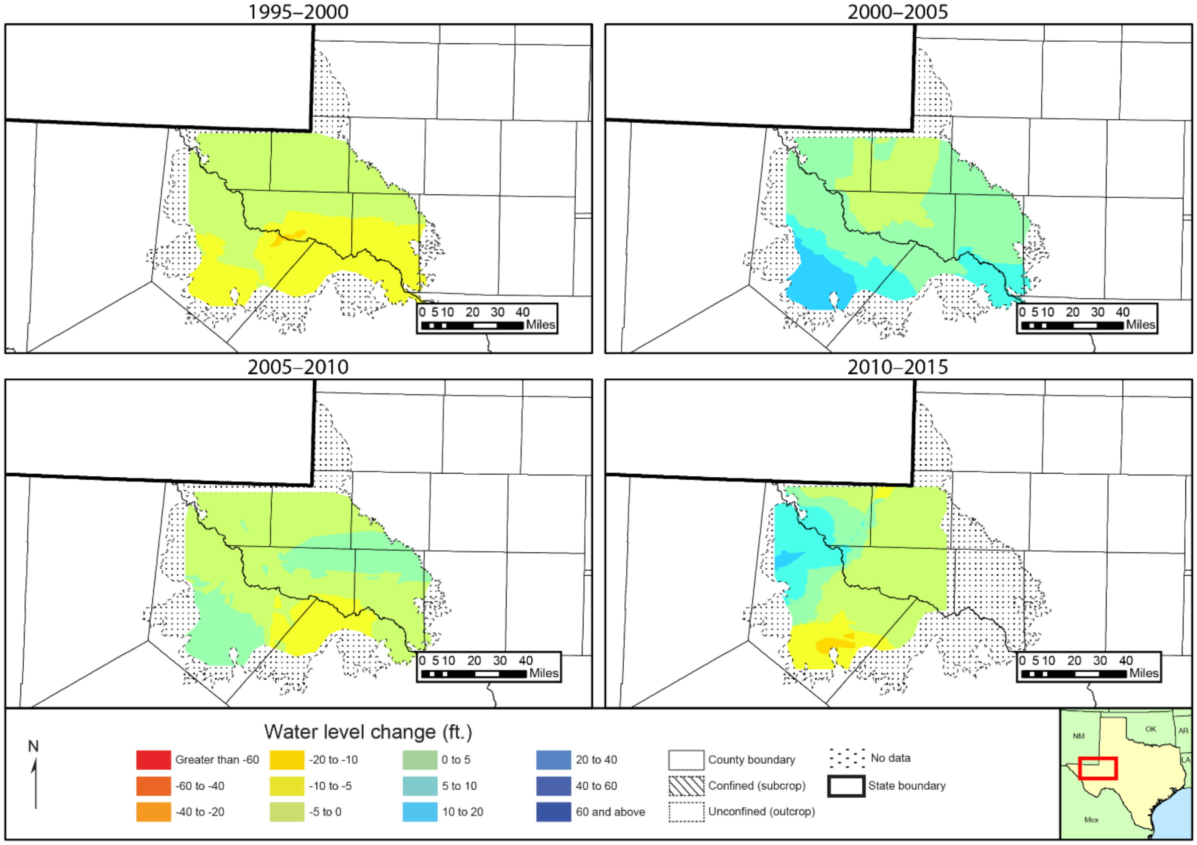


Figure 6-31. Water-level changes in the Pecos Valley Aquifer, 1995 to 2015.

Water quality

Water quality in the Pecos Valley Aquifer is highly variable, though it is typically hard and generally has lower total dissolved solids concentrations in the Monument Draw Trough than in the Pecos Trough. Total dissolved solids concentrations in groundwater from the Monument Draw Trough are usually less than 1,000 milligrams per liter (Figure 6-32). The aquifer is characterized by high levels of chloride and sulfate, frequently in excess of secondary drinking water standards. Although groundwater in the Monument Valley Trough is generally fresher, arsenic, fluoride, and radionuclides are more frequently detected in excess of drinking water standards there than in the Pecos Trough (Reedy and others, 2011). Arsenic and fluoride concentrations tend to decrease with increasing well depth.

Water quality is affected by recharge from the Pecos River, which has a high total dissolved solids content acquired by dissolution of evaporites in the river basin (Miyamoto and others, 2006). Water quality may be degraded by cross-formational flow from underlying saline aquifers induced by pumping in the Monument Draw Trough (Jones, 2004). East of the Pecos River, oil field brines and agricultural runoff have a significant effect on the groundwater quality of the Pecos Valley Aquifer (Ashworth, 1990).

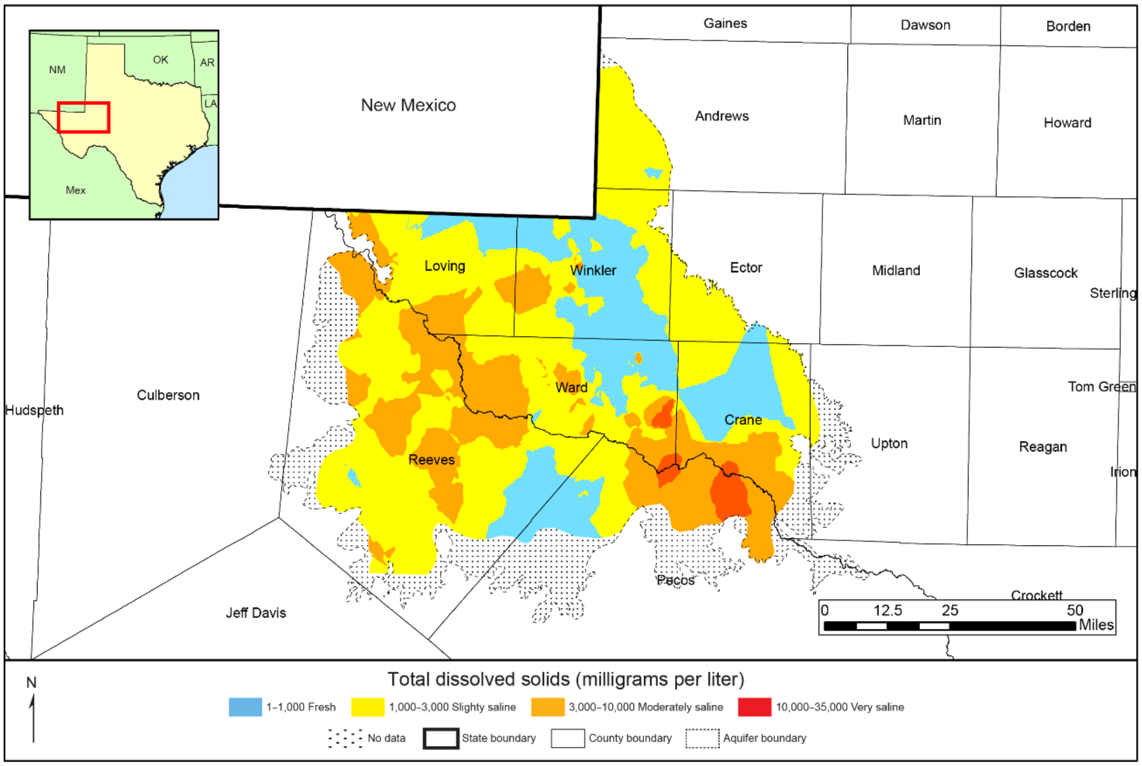


Figure 6-32. Total dissolved solids in the Pecos Valley Aquifer.

6.8 Seymour Aquifer

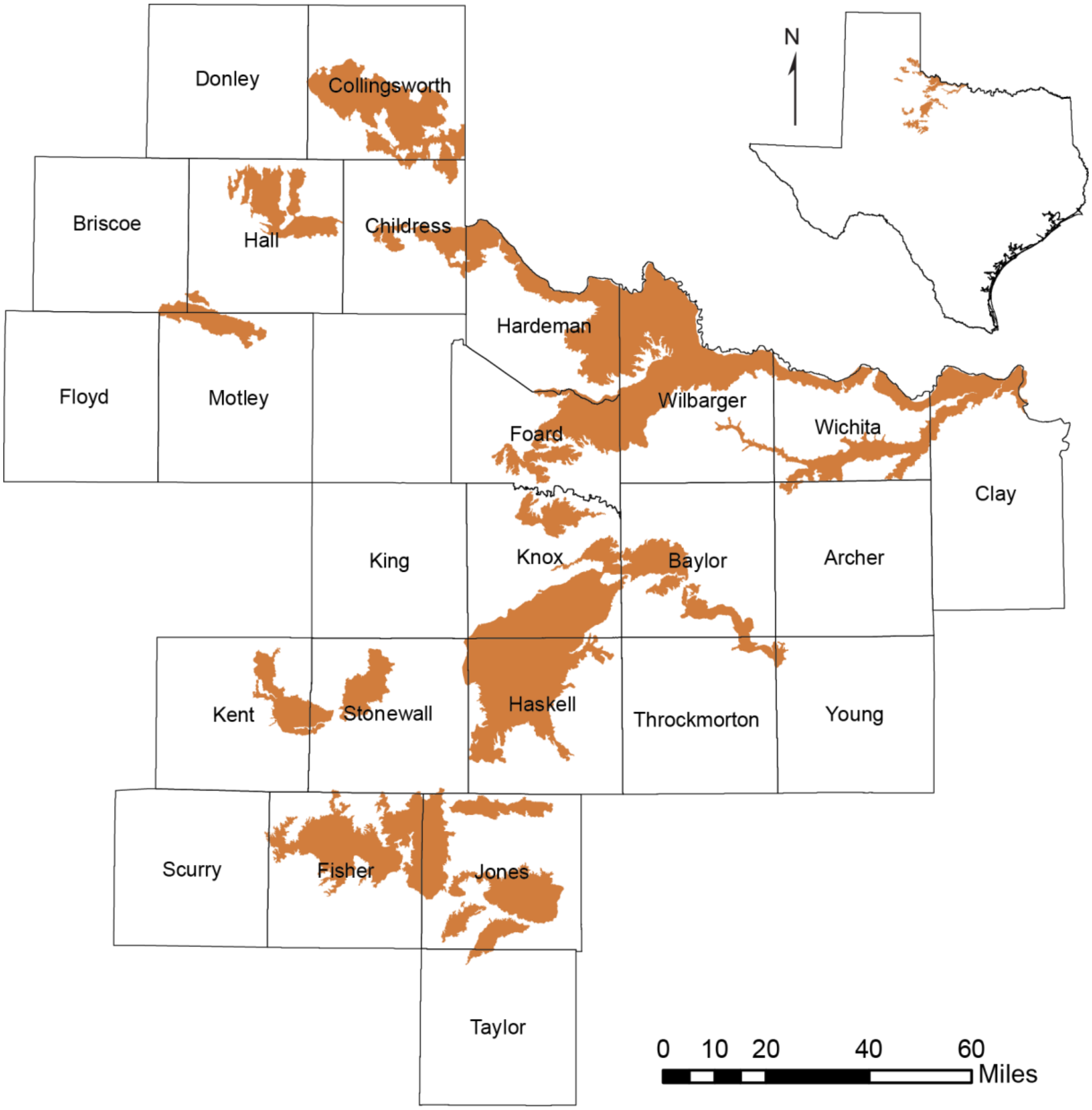


Figure 6-33. Extent of the Seymour Aquifer.

Aquifer characteristics

- Aquifer type: unconfined
- Area of aquifer: 3,374 square miles
- Proportion of aquifer with groundwater conservation districts: 62 percent
- Number of counties containing the aquifer: 25

Geology and hydrogeology

The Seymour Aquifer is a major aquifer extending across north central Texas (Figure 6-33). The aquifer consists of Quaternary-age, alluvial sediments unconformably overlying westerly-dipping Permian-age rocks (Figure 6-34). The Seymour Aquifer is composed of discontinuous beds of poorly sorted gravel, conglomerate, sand, and silty clay eroded from the High Plains and deposited by eastward moving streams (R.W. Harden and Associates, 1978; Nordstrom, 1991; Duffin and Beynon, 1992). The sediments likely originally blanketed the entire region but were eroded by recent streams, leaving only the isolated areas, or "pods," of sediment found today (Ogilbee and Osborne, 1962; Preston, 1978; Price, 1978). The sediments generally coarsen downward to the basal section of coarse sand and gravel. This basal section is the predominant water-producing zone.

Groundwater in the Seymour Aquifer is unconfined. Water is contained in pods of alluvium as much as 360 feet thick. The average recharge rate is 2 inches per year. It is reported that prior to significant land clearing and farming, the Seymour Aquifer was not a productive aquifer; the saturated thickness was inadequate to support pumping. Evapotranspiration losses decreased after the land was cleared, resulting in greater recharge and a gradual increase in the saturated thickness of the aquifer.

The geometric mean of the horizontal hydraulic conductivity for the aquifer is 68.5 feet per day. The specific yield of the Seymour Aquifer is estimated to range from 11 to 15 percent (Ewing and others, 2004).

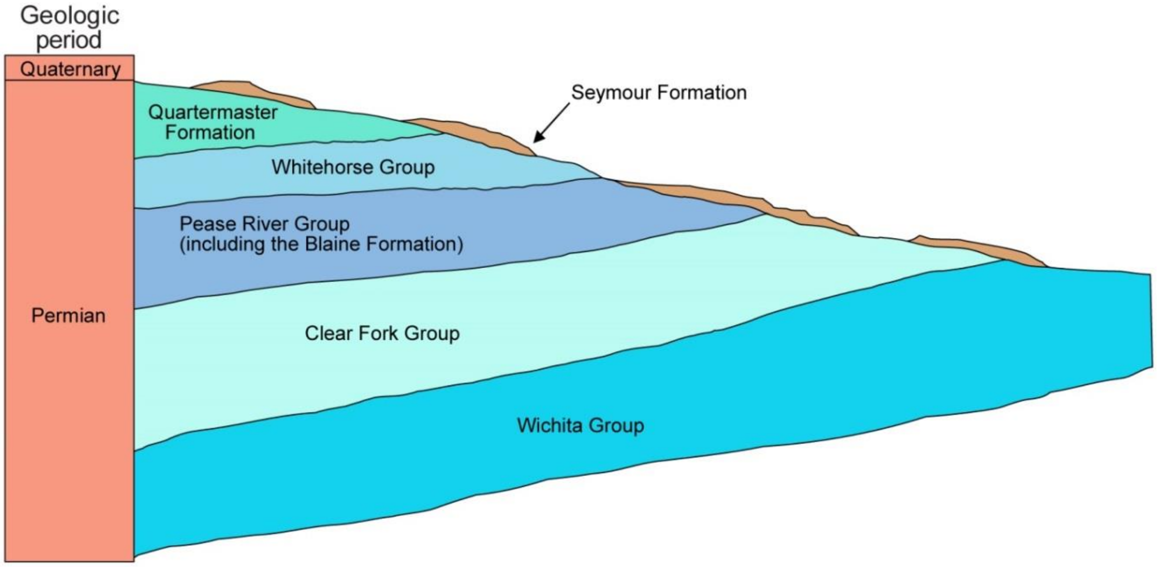


Figure 6-34. **Generalized stratigraphy of the Seymour Aquifer and underlying Permian rocks (modified from Ewing and others, 2004).**

Flows to surface water and other aquifers

Groundwater flow within the Seymour Aquifer is controlled by topography, structure, and permeability variation. Groundwater discharges to springs and seeps, local creeks, and major streams throughout the area, contributing to the baseflow of the streams. More than 600 springs and seeps are documented along the boundary of the Seymour Formation. Discharge directly to streams occurs in the younger Quaternary alluvium portions of the Seymour Aquifer where the aquifer is in direct contact with streams (Ewing and others, 2004). Table 6-22 summarizes groundwater flow from the Seymour Aquifer to surface water.

In addition, discharge from the Seymour Aquifer occurs by cross-formational flow into the underlying units. Cross-formational flow from the Seymour Aquifer is expected to be lowest in the eastern portion of the model domain where the Seymour Aquifer overlies the Wichita and Clear Fork groups of the Permian System. Some measurable discharge from the Seymour Aquifer to the Clear Fork Group may occur in Jones County (Price, 1978). In the north central region of the model domain, where the Seymour Aquifer overlies the Blaine Aquifer, appreciable, localized cross-formational flow to the Blaine Aquifer may occur (Ewing and others, 2004). Table 6-23 summarizes flow between the Seymour and Blaine aquifers.

Table 6-22. Summary of groundwater flow from the Seymour Aquifer to surface water, by county.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Archer	5	0.1	0
Baylor	136	1.1	0.1
Briscoe	10	0	0
Childress	82	0.4	0.1
Clay	106	3.7	1
Collingsworth	276	2.4	0.6
Donley	0	0	0
Fisher	283	2.1	0.4
Floyd	0	0	0
Foard	186	2.1	0.4
Hall	147	0.4	0.1
Hardeman	241	3.2	0.8
Haskell	370	3.7	0.9
Jones	326	3.3	0.7
Kent	80	0.3	0.1
King	0	0	0
Knox	307	4.3	1.2
Motley	54	0.4	0.1
Scurry	1	0	0
Stonewall	96	0.5	0.1
Taylor	5	0	0
Throckmorton	16	0.1	0
Wichita	189	4.4	0.9
Wilbarger	449	6.7	1.5
Young	7	0.1	0
Total	**3,372**	**39**	**9**

Table 6-23. Model estimates of inter-aquifer flows between the Seymour Aquifer and the Blaine Aquifer.

Flow from	Flow to	Total flow (acre-feet per year)
Seymour Aquifer	Blaine Aquifer	7,162
Blaine Aquifer	Seymour Aquifer	34,072

Water quantity

Total storage in the Seymour Aquifer is estimated to be more than 5 million acre-feet. Recoverable storage is estimated to be between 25 and 75 percent of the total, about 1.2 million to 3.8 million acre-feet (Table 6-24). Figure 6-35 shows changes in water levels in the Seymour Aquifer from 1995 to 2015.

Table 6-24. Total estimated recoverable storage in the Seymour Aquifer, by groundwater management area, in acre-feet.

Groundwater management area	Total storage	25 percent of storage	75 percent of storage
1	760	190	570
2	57,000	14,250	42,750
6	5,070,100	1,267,525	3,802,575
7	610	153	458
Total	**5,128,470**	**1,282,118**	**3,846,353**

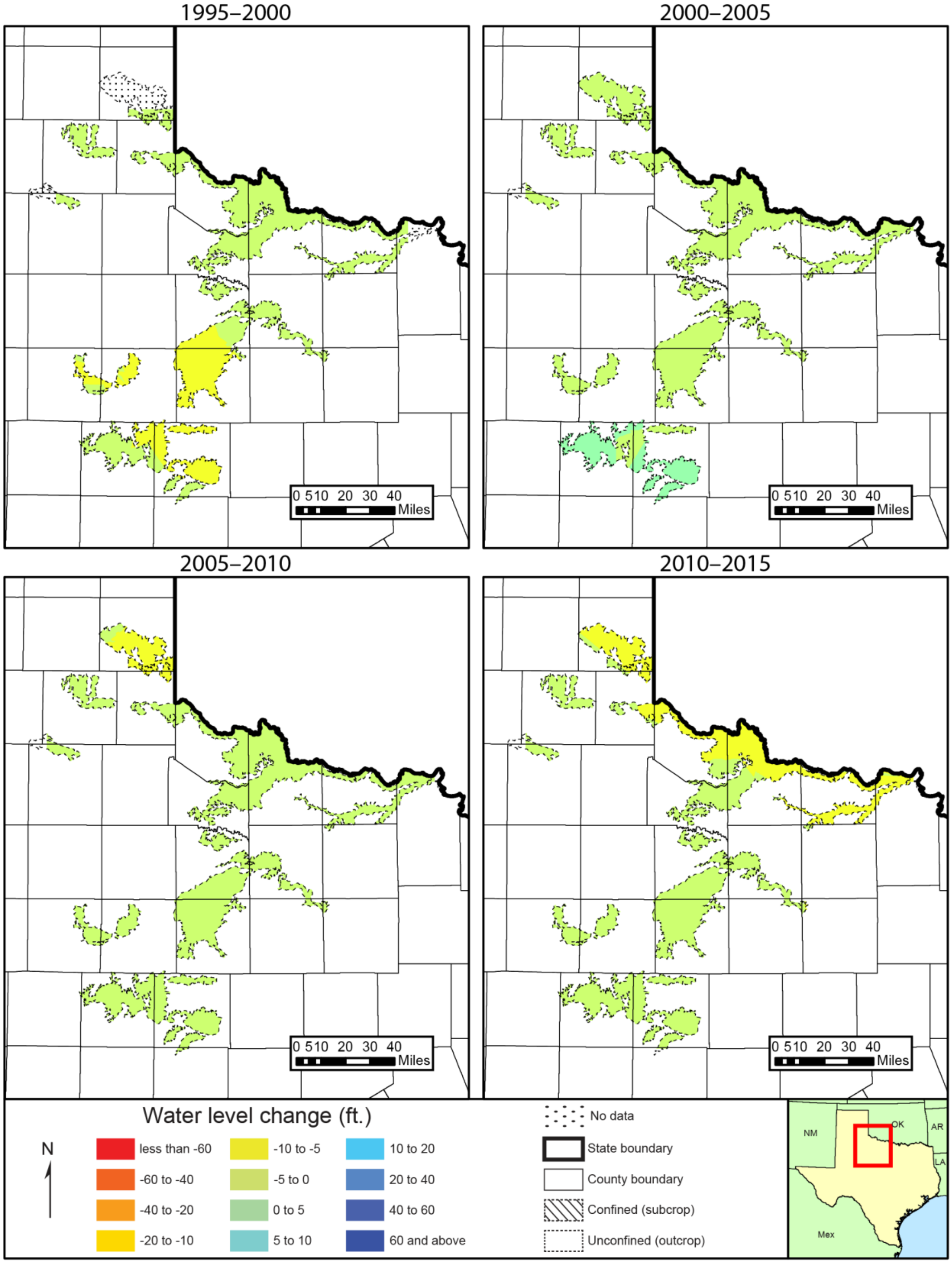


Figure 6-35. **Water-level changes in the Seymour Aquifer, 1995 to 2015.**

Water quality

Water quality ranges from fresh to slightly saline, with total dissolved solids concentrations ranging from about 100 to 3,000 milligrams per liter. However, moderately to very saline water exists in localized areas, with total dissolved solids concentrations ranging from 3,000 to more than 10,000 milligrams per liter (Figure 6-36).

Throughout its extent, the aquifer is affected by nitrate in excess of primary drinking water standards. High nitrate concentrations are attributed to oxidation of soil organic nitrogen during initial cultivation followed by leaching of fertilizers on cultivated land. Excessive chloride and sulfate also occur throughout the aquifer. The Haskell-Knox counties pod of the aquifer has the highest probability for exceeding any primary drinking water standard (Reedy and others, 2011).

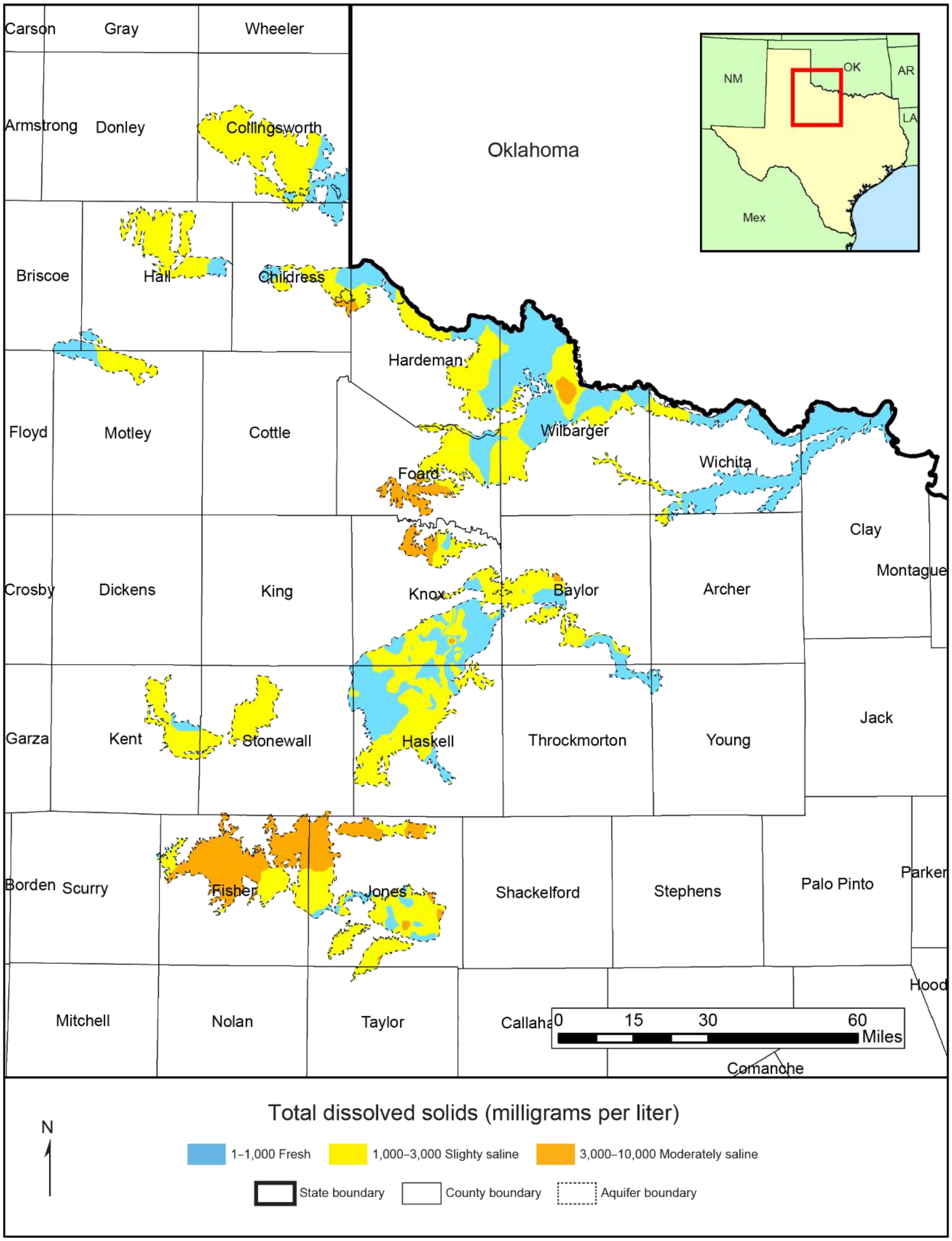


Figure 6-36. Total dissolved solids in the Seymour Aquifer.

6.9 Trinity Aquifer

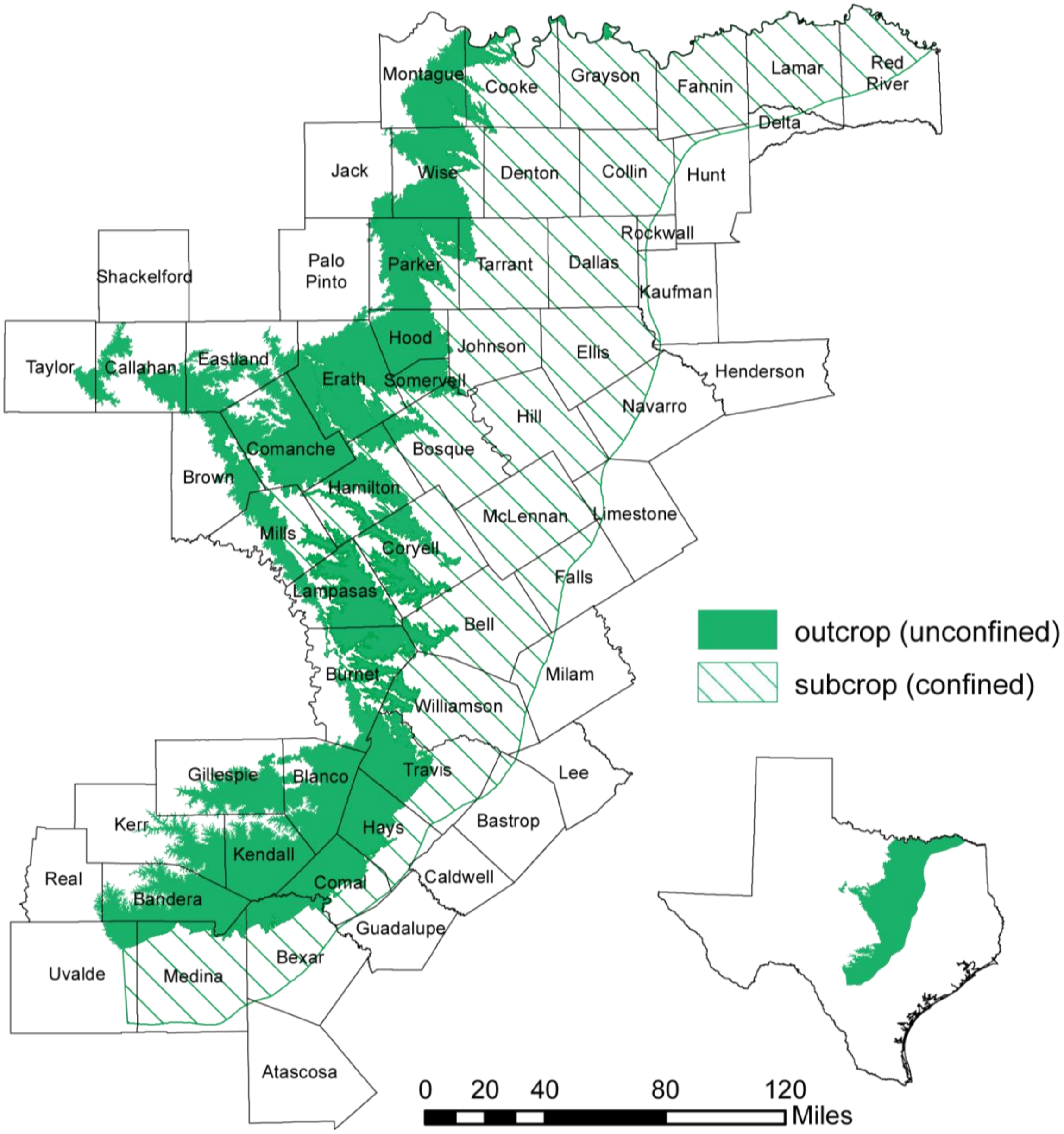


Figure 6-37. Extent of the Trinity Aquifer.

Aquifer characteristics

- Aquifer type: confined and unconfined
- Area of outcrop: 10,692 square miles
- Area in subsurface: 21,308 square miles
- Proportion of aquifer with groundwater conservation districts: 82 percent
- Number of counties containing the aquifer: 61

Geology and hydrogeology

The Trinity Aquifer is a major aquifer extending across much of the central and northeastern part of the state (Figure 6-37). It is composed of several water-bearing formations within the Trinity Group. Although referred to differently in different parts of the state, they include the Antlers, Glen Rose, Paluxy, Twin Mountains, and Travis Peak. These formations consist of limestones, sands, clays, gravels, and conglomerates. Their combined freshwater saturated thickness averages about 600 feet in North Texas and about 1,900 feet in Central Texas (Figure 6-38 and Figure 6-39).

Sand distribution and thickness largely controls the productivity of the aquifer. The depositional environment in the Cretaceous Period resulted in a layered system of aquifers and aquitards in the northern Trinity Group. These sandstones were deposited in two contrasting environments, resulting in fluvial and shoreline water-bearing sandstones (Kelly and others, 2014).

The hydraulic properties of the formations making up the northern Trinity Aquifer vary considerably. The median hydraulic conductivities in the calibrated groundwater model for the Woodbine, Paluxy, Hensell, and Hosston aquifers are 0.15, 0.47, 1.67, and 2.27 feet per day, respectively. Storativity ranges over several orders of magnitude between layers and geographically within each layer, with values from 1×10^{-6} to 3×10^{-3}. The specific yield of the unconfined portion of the aquifer was modeled as 0.1. In Central Texas, calibrated values of the specific yield were 0.0005 for the upper portion of the Trinity Aquifer and 0.0008 for the middle and lower portions of the Trinity Aquifer (Kelly and others, 2014).

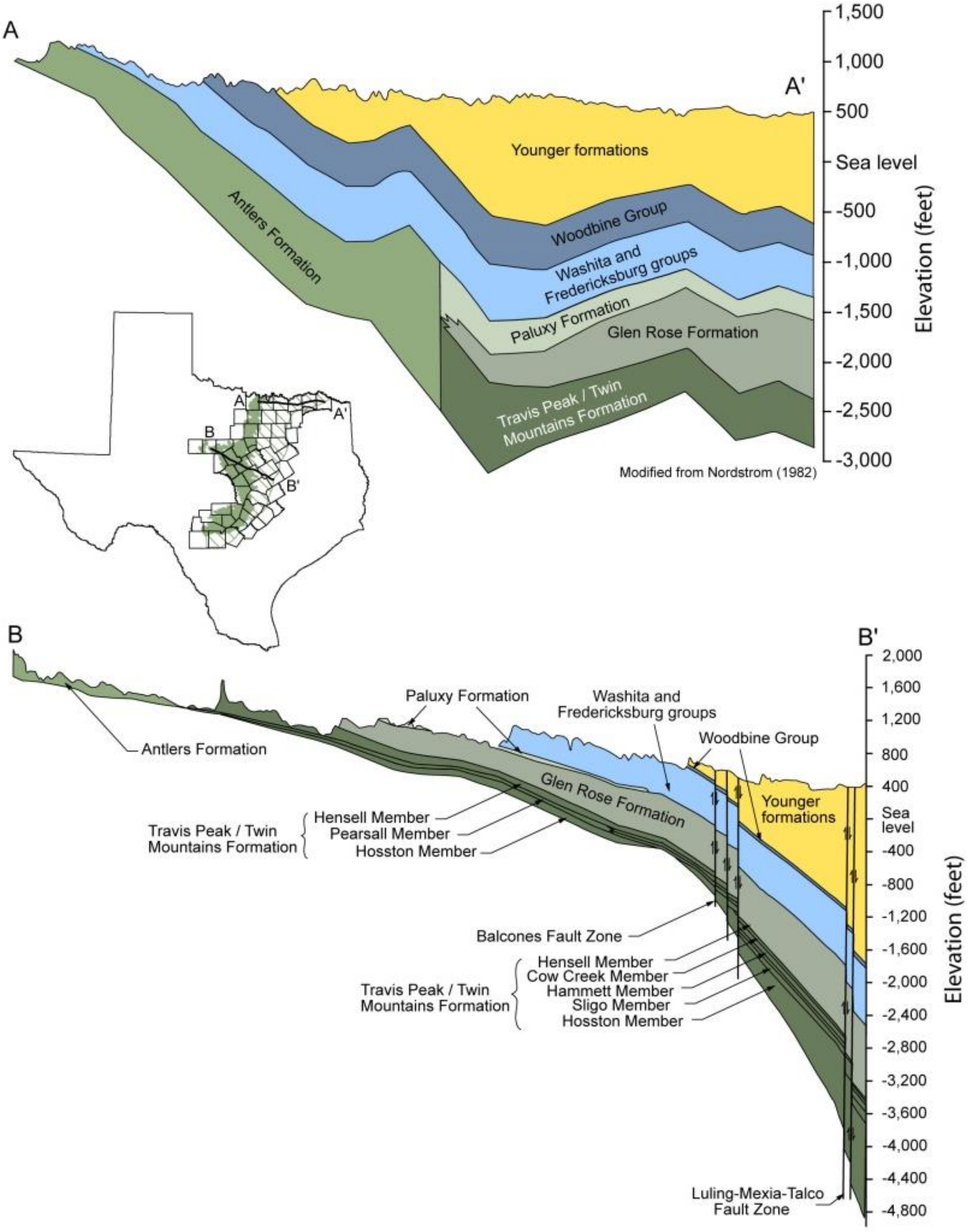


Figure 6-38. Structural cross-sections of the northern Trinity Aquifer, shown in shades of green (modified from Klemt and others; 1975; Nordstrom, 1982).

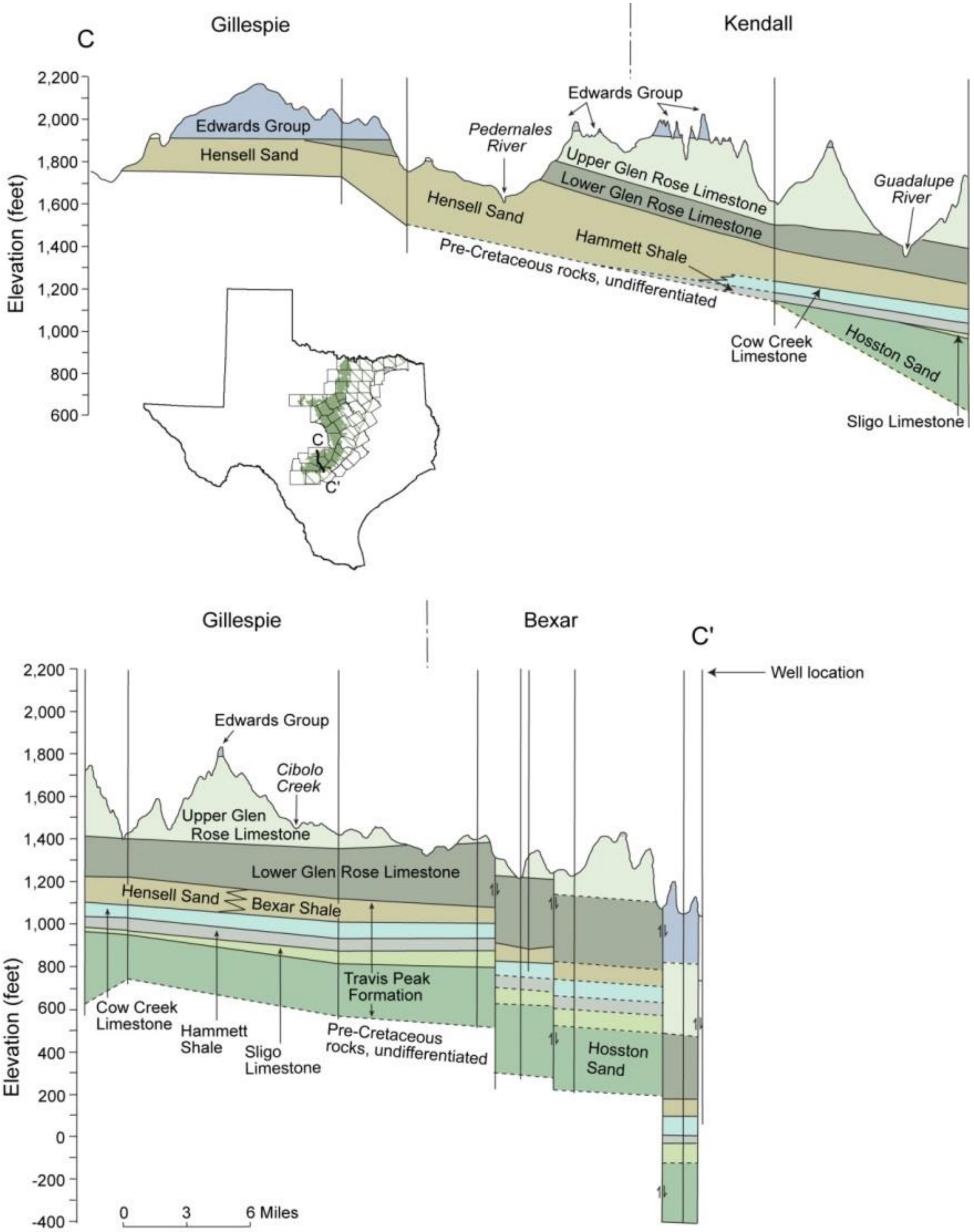


Figure 6-39. **Structural cross-section of the Trinity Aquifer in the Hill Country, including rocks from the Upper Glen Rose Formation to the Hosston Sand (modified from Ashworth, 1983; Mace and others, 2000b).**

Flows to surface water and other aquifers

The Trinity Aquifer discharges to a large number of springs, with most discharging less than 10 cubic feet per second. Table 6-25 summarizes groundwater flow from the Trinity Aquifer to surface water as baseflow. Table 6-26 shows groundwater availability model estimates of total flow and average annual flow between the Trinity Aquifer and other aquifers.

Table 6-25. Summary of groundwater flow from the Trinity Aquifer to surface water, by county.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Bandera	589	81.7	26.1
Bell	67	5.9	1.4
Bexar	178	10.9	2.5
Blanco	571	57.6	14.9
Bosque	85	4	0.5
Brown	225	5.1	0.7
Burnet	434	38.8	5.9
Callahan	276	2.8	0.2
Comal	322	41.5	14.6
Comanche	760	23.9	3
Cooke	122	5.3	0.8
Coryell	303	16.4	2.8
Denton	3	0.2	0
Eastland	351	5.5	0.5
Erath	817	30.8	4.3
Gillespie	380	26.9	10.8
Grayson	15	0.9	0.2
Hamilton	325	13.8	1.9
Hays	353	57.3	13
Hood	384	18.2	3.1
Jack	53	1.3	0.1
Johnson	11	0.4	0.1
Kendall	573	73	23.5
Kerr	274	42.5	19.7
Lampasas	456	32.1	5.1
Llano	0	0	0
Medina	121	11.9	3

Table 6-25. Summary of groundwater flow from the Trinity Aquifer to surface water, by county.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Mills	261	10.4	1.6
Montague	416	15	1.7
Palo Pinto	14	0.2	0
Parker	565	23.2	3.3
Real	13	1.9	0.6
Shackelford	0	0	0
Somervell	142	9.5	1.6
Tarrant	58	2.6	0.3
Taylor	49	0.4	0
Travis	393	51.1	8.2
Uvalde	84	9.8	2.7
Williamson	70	8	1.2
Wise	594	21.7	2.6
Total	**10,707**	**763**	**183**

Table 6-26. Model estimates of inter-aquifer flows between the Trinity Aquifer and other major aquifers.

Flow from	Flow to	Total flow (acre-feet per year)
Trinity Aquifer	Edwards (Balcones Fault Zone) Aquifer	61,463
Trinity Aquifer	Edwards-Trinity (Plateau) Aquifer	20,546
Trinity Aquifer	Ellenburger-San Saba Aquifer	1,285
Trinity Aquifer	Marble Falls Aquifer	144
Edwards (Balcones Fault Zone) Aquifer	Trinity Aquifer	9,381
Edwards-Trinity (Plateau) Aquifer	Trinity Aquifer	21,848
Hickory Aquifer	Trinity Aquifer	64

Water quantity

Total storage in the Trinity Aquifer is estimated to be more than 1.4 billion acre-feet. Recoverable storage is estimated to be between 25 and 75 percent of the total, about 357.2 million and 1.0 billion acre-feet (Table 6-27). Figure 6-40 shows water-level changes in the Trinity Aquifer from 1995 to 2015.

Table 6-27. Total estimated recoverable storage in the Trinity Aquifer, by groundwater management area, in acre-feet.

Groundwater management area	Total storage	25 percent of storage	75 percent of storage
2	23,710,000	5,927,500	17,782,500
6	471,000	117,750	353,250
7	523,000	130,750	392,250
8	1,359,530,000	339,882,500	1,019,647,500
9	5,280,000	1,320,000	3,960,000
10	23,057,000	5,764,250	17,292,750
11	500,000	125,000	375,000
12	11,100,000	2,775,000	8,325,000
13	4,695,000	1,173,750	3,521,250
Total	**1,428,866,000**	**357,216,500**	**1,071,649,500**

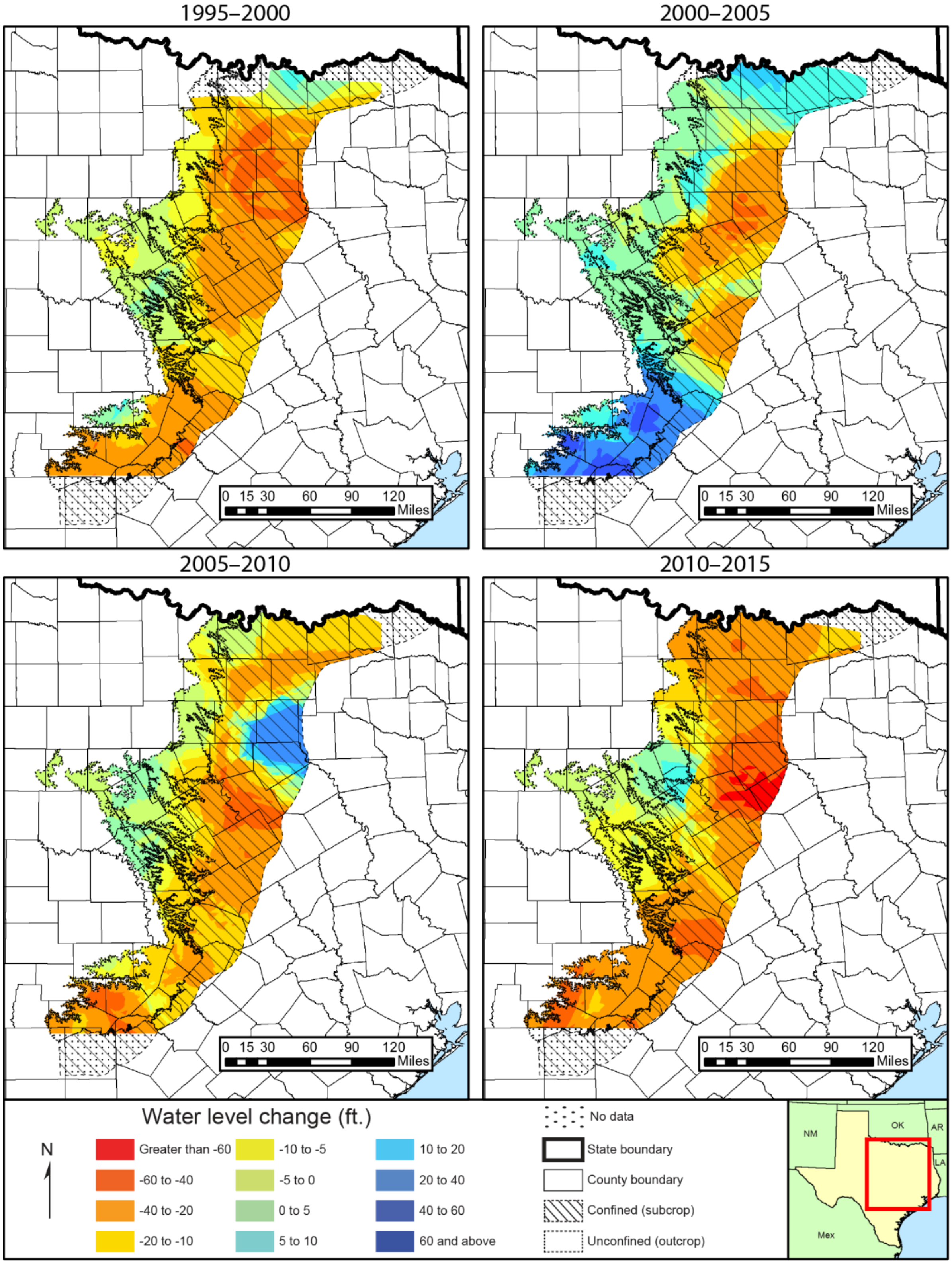


Figure 6-40. **Water-level changes in the Trinity Aquifer, 1995 to 2015.**

Water quality

In general, groundwater is fresh but very hard in the outcrop of the aquifer. Total dissolved solids concentrations increase from less than 1,000 milligrams per liter in the outcrop area to between 1,000 and 5,000 milligrams per liter, or slightly to moderately saline, down-dip as the depth to the aquifer increases (Figure 6-41). High sulfate and chloride concentrations in the Trinity Aquifer are attributed to dissolution of evaporite beds in the upper unit of the Glen Rose Formation and in the Middle Trinity Aquifer to gypsum and evaporite beds in the Cow Creek Member of the Travis Peak Formation.

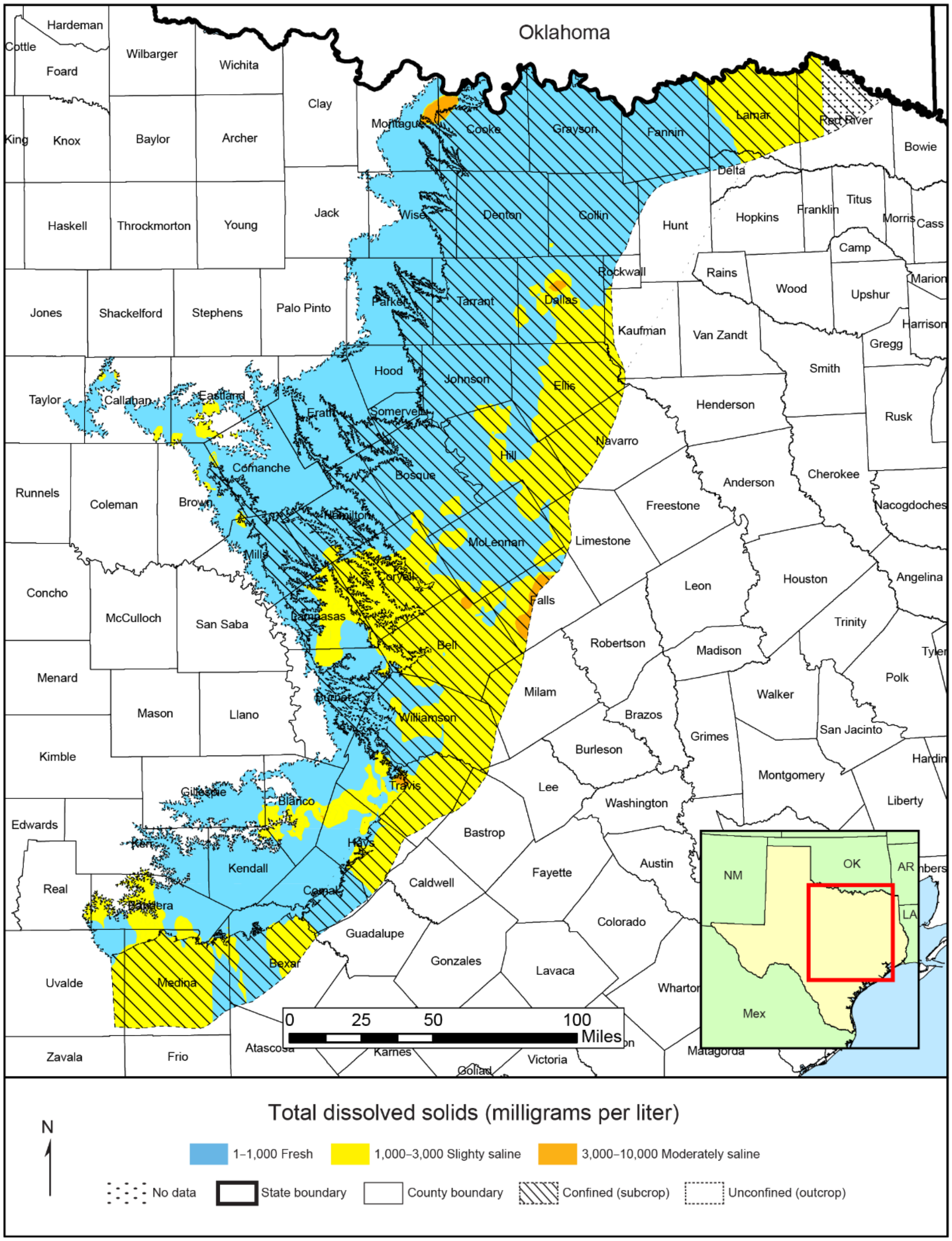


Figure 6-41. **Total dissolved solids in the Trinity Aquifer, based on samples from 5,999 wells. Water quality in individual formations within the Trinity Aquifer may vary from the distribution shown here.**

6.10 Blaine Aquifer

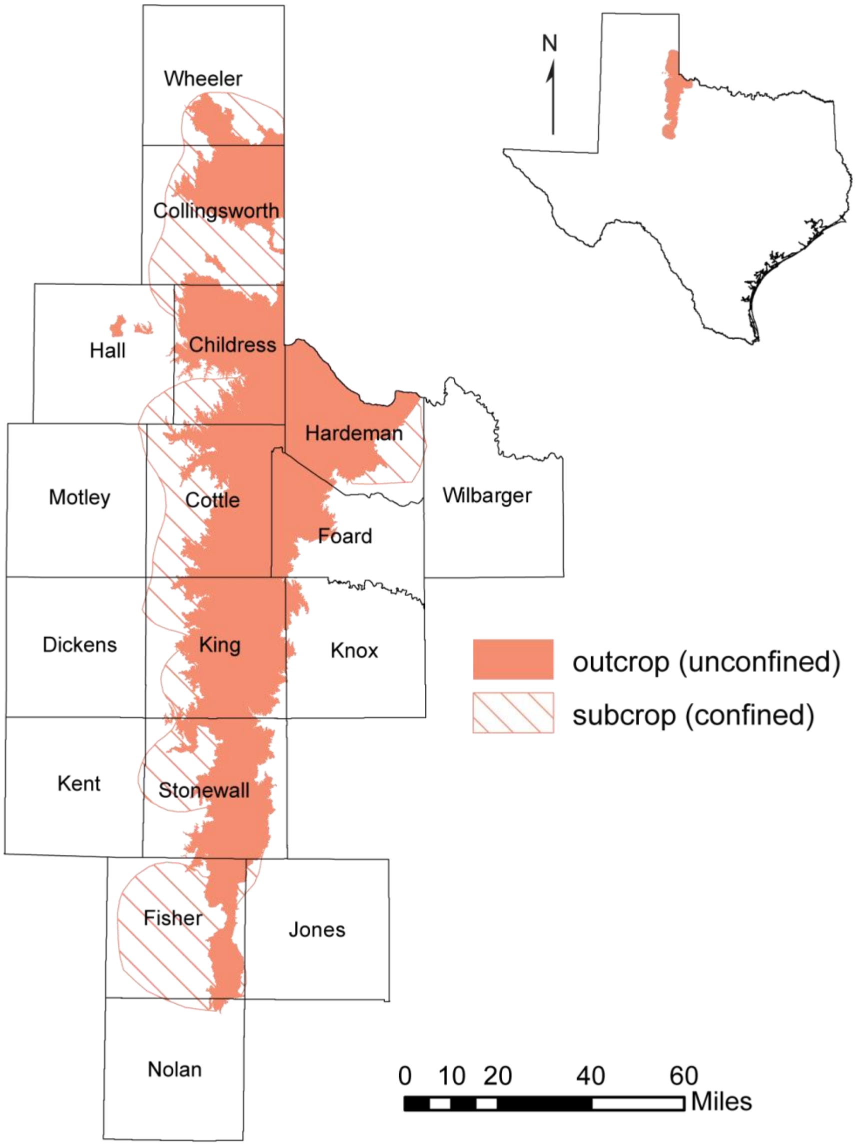


Figure 6-42. Extent of the Blaine Aquifer.

Aquifer characteristics

- Aquifer type: confined and unconfined
- Area of outcrop: 3,443 square miles
- Area of subsurface: 2,234 square miles
- Proportion of aquifer with groundwater conservation districts: 74 percent
- Number of counties containing the aquifer: 17

Geology and hydrogeology

The Blaine Aquifer is a minor aquifer located along the eastern edge of the High Plains in North Texas (Figure 6-42). The aquifer is part of the Permian Blaine Formation, which is composed of red silty shale, gypsum, anhydrite, salt, and dolomite. The formation consists of cycles of marine and non-marine sediments deposited in a broad, shallow sea that once covered the southwestern United States. Saturated thickness reaches 300 feet in the aquifer, but freshwater saturated thickness averages 137 feet (Figure 6-43). Groundwater occurs primarily in solution channels and caverns within the beds of anhydrite and gypsum; dissolution of these minerals contributes to the overall poor quality of the water (Hopkins and Muller, 2011).

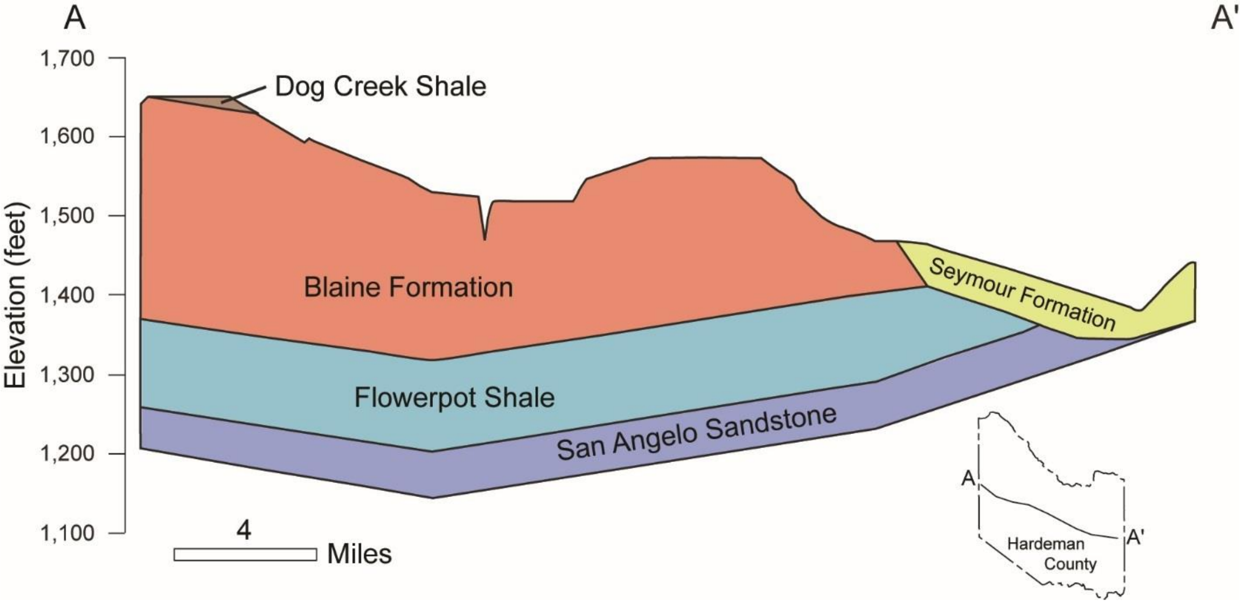


Figure 6-43. **Structural cross-section of the Blaine Aquifer from the west to the east across Hardeman County (from Maderak, 1972).**

Flows to surface water and other aquifers

Many springs originate from the Blaine Formation and contribute to surface water (Ewing and others, 2004). A summary of baseflow in the outcrop areas of the Blaine Aquifer is reported in Table 6-28. Groundwater availability model analysis estimates a total flow of 34,072 acre-feet per year from the Blaine Aquifer to the Seymour Aquifer and a total flow of 7,162 acre-feet per year from the Seymour Aquifer to the Blaine Aquifer (Table 6-29). While the Seymour Aquifer is made up of several separate "pods" with independent flow systems, in general the low sulfate concentrations in the Seymour Aquifer suggest that inter-aquifer flow is primarily from the Seymour Aquifer into the Blaine Aquifer (Ewing and others, 2004).

Table 6-28. Summary of groundwater flow from the Blaine Aquifer to surface water, by county.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Childress	462	3.2	0.8
Collingsworth	325	6.2	2.5
Cottle	501	5.4	2.2
Fisher	124	0.9	0.2
Foard	243	3.8	1.6
Hall	11	0	0
Hardeman	375	4.9	1
Jones	2	0	0
King	602	11.3	5.7
Knox	35	0.9	0.4
Nolan	7	0	0
Stonewall	437	2.6	0.3
Wheeler	85	2.1	1.1
Total	**3,209**	**41**	**16**

Table 6-29. Model estimates of inter-aquifer flows between the Blaine Aquifer and Seymour Aquifer.

Flow from	Flow to	Total flow (acre-feet per year)
Blaine Aquifer	Seymour Aquifer	34,072
Seymour Aquifer	Blaine Aquifer	7,162

Water quantity

Total storage in the Blaine Aquifer is estimated to be more than 171 million acre-feet. Recoverable storage in the aquifer is estimated to be between 25 and 75 percent of the total, about 42.9 million to 128.7 million acre-feet (Table 6-30).

Table 6-30. Total estimated recoverable storage in the Blaine Aquifer, by county, in acre-feet.

County	Total storage	25 percent of storage	75 percent of storage
Childress	18,000,000	4,500,000	13,500,000
Collingsworth	29,000,000	7,250,000	21,750,000
Cottle	22,000,000	5,500,000	16,500,000
Dickens	35,000	8,750	26,250
Fisher	15,000,000	3,750,000	11,250,000
Foard	5,900,000	1,475,000	4,425,000
Hall	2,500,000	625,000	1,875,000
Hardeman	10,000,000	2,500,000	7,500,000
Jones	880,000	220,000	660,000
Kent	490,000	122,500	367,500
King	24,000,000	6,000,000	18,000,000
Knox	810,000	202,500	607,500
Motley	110,000	27,500	82,500
Nolan	260,000	65,000	95,000
Stonewall	36,000,000	9,000,000	27,000,000
Wheeler	6,700,000	1,675,000	5,025,000
Wilbarger	1,400	350	1,050
Total	**171,686,400**	**42,921,600**	**128,764,800**

Water quality

Groundwater in the Blaine Aquifer is typically brackish. Although some wells contain slightly saline water, with total dissolved solids between 1,000 and 3,000 milligrams per liter, most contain moderately saline water, with total dissolved solids between 3,000 and 10,000 milligrams per liter, exceeding secondary drinking water standards for Texas (Hopkins and Muller, 2011). Sulfate values are also well in excess of the secondary drinking water standard of 300 milligrams per liter. Figure 6-44 shows the distribution of total dissolved solids in the Blaine Aquifer.

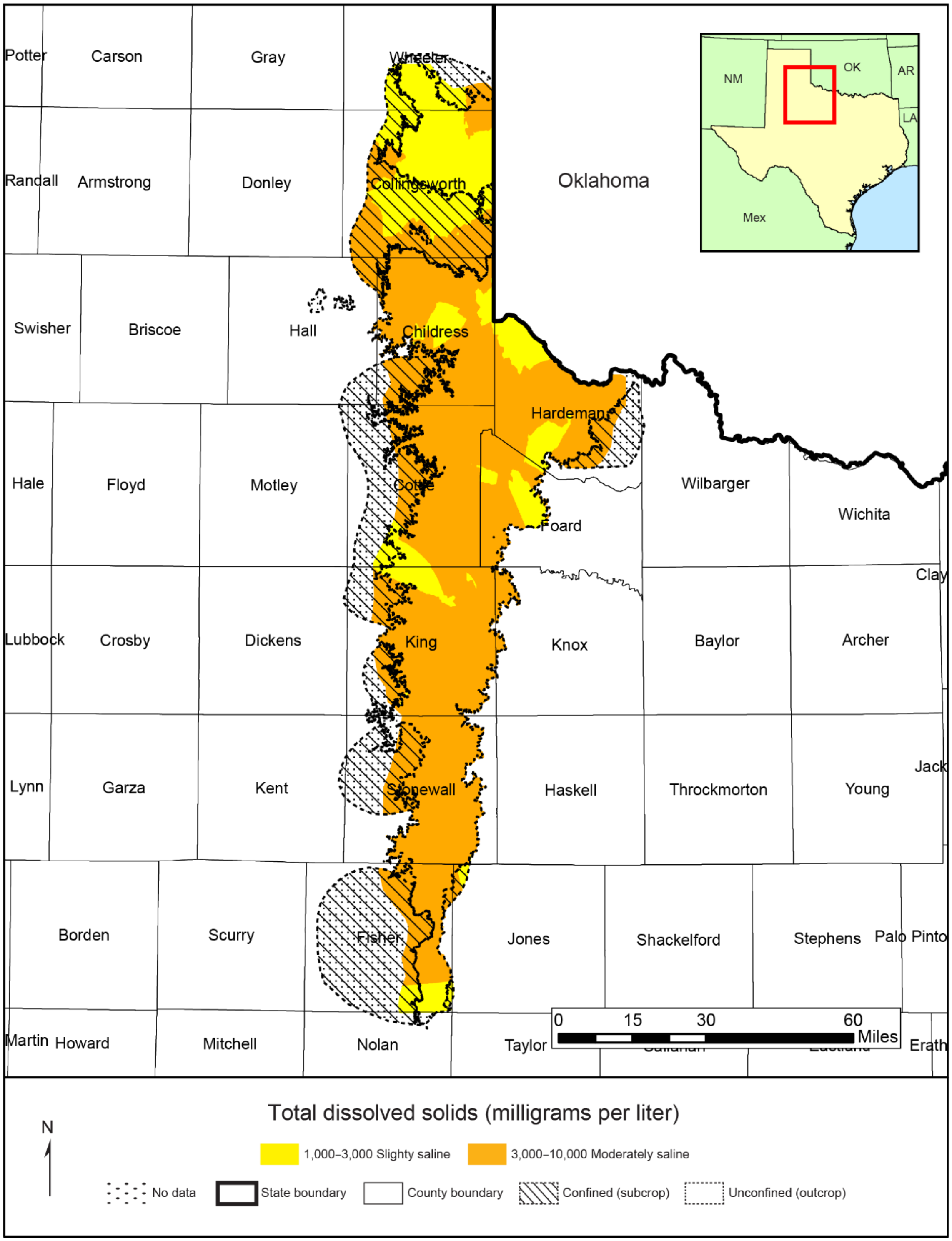


Figure 6-44. Total dissolved solids in the Blaine Aquifer.

6.11 Blossom Aquifer

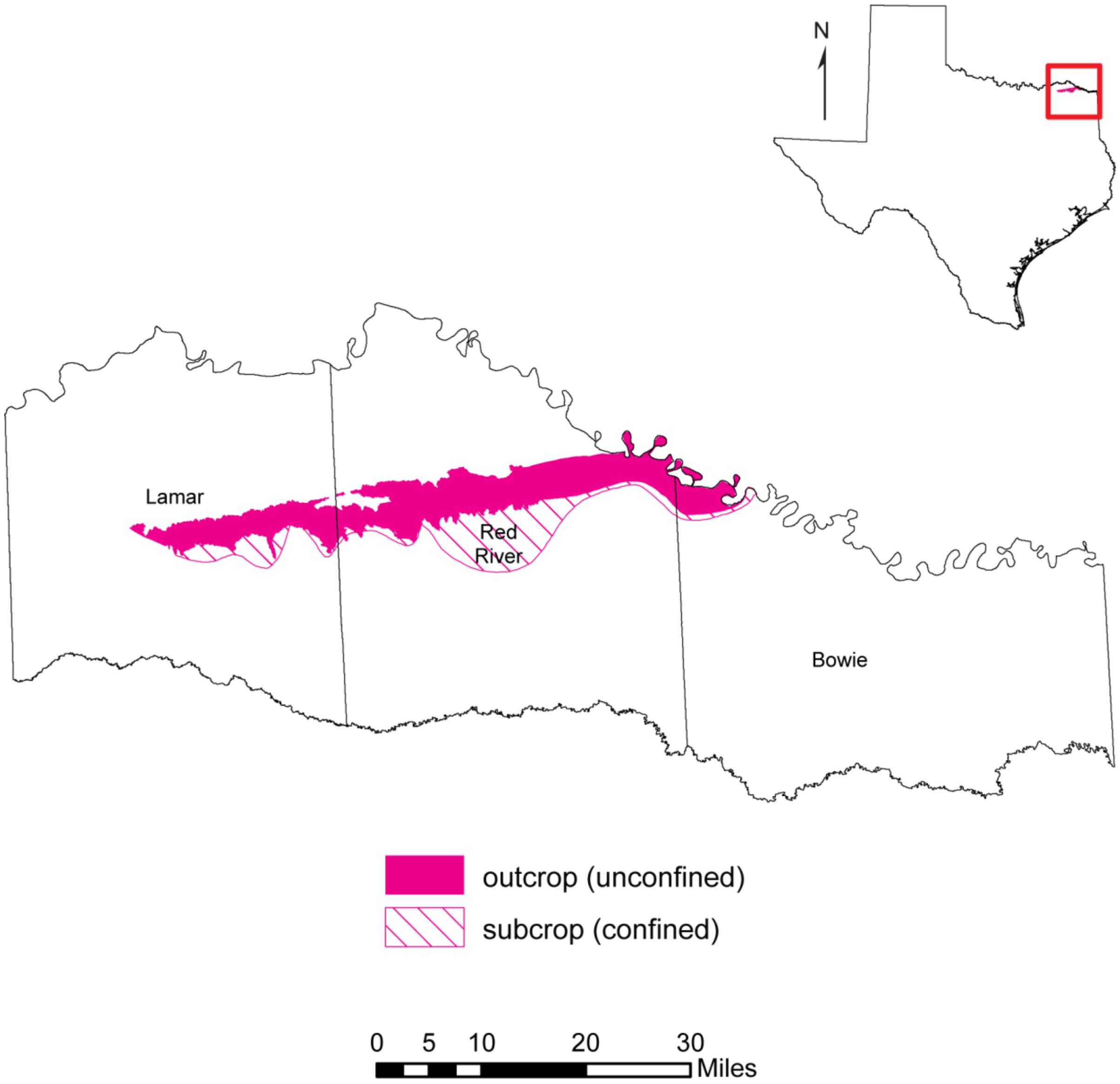


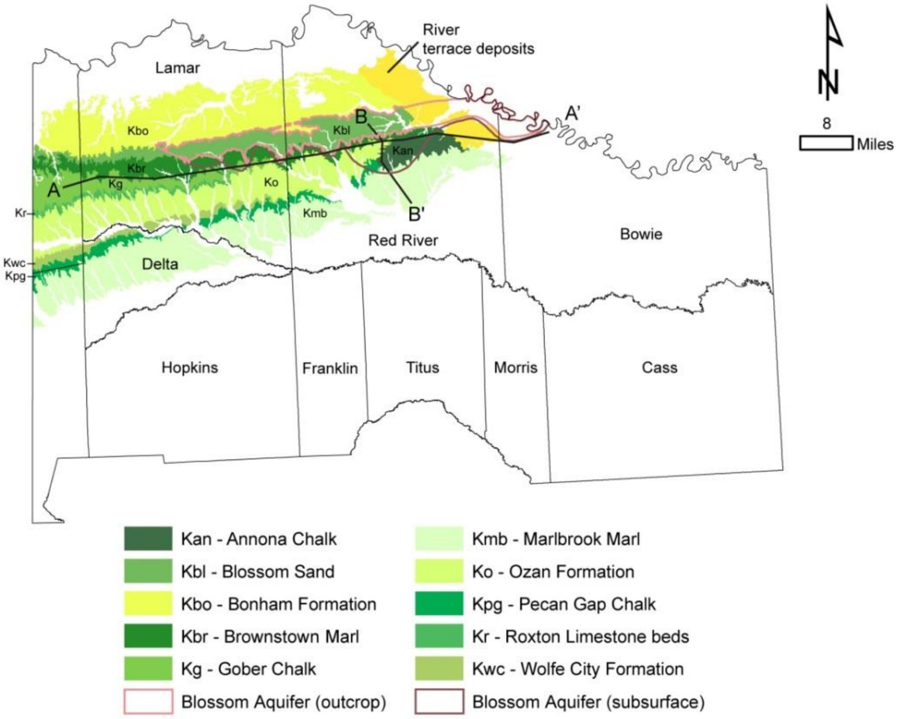
Figure 6-45. Extent of the Blossom Aquifer.

Aquifer characteristics

- Aquifer type: confined and unconfined
- Area of outcrop: 182 square miles
- Area of subsurface: 95 square miles
- Proportion of aquifer with groundwater conservation districts: 0 percent
- Number of counties containing the aquifer: 3

Geology and hydrogeology

The Blossom Aquifer is a minor aquifer located in Bowie, Red River, and Lamar counties in the northeast corner of Texas (Figure 6-45). The aquifer consists of the Blossom Sand Formation, composed of alternating sequences of sand and clay. In places, the aquifer is as much as 400 feet thick, although no more than about one-third of this thickness consists of sand, and freshwater saturated thickness averages 25 feet (Figure 6-46 and Figure 6-47).



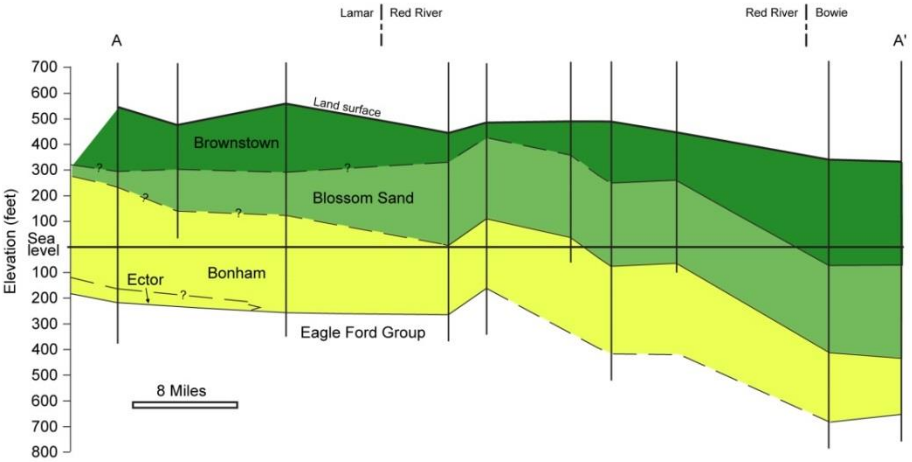


Figure 6-46. East to west geologic cross-section along the Blossom Aquifer (modified from McLaurin, 1988).

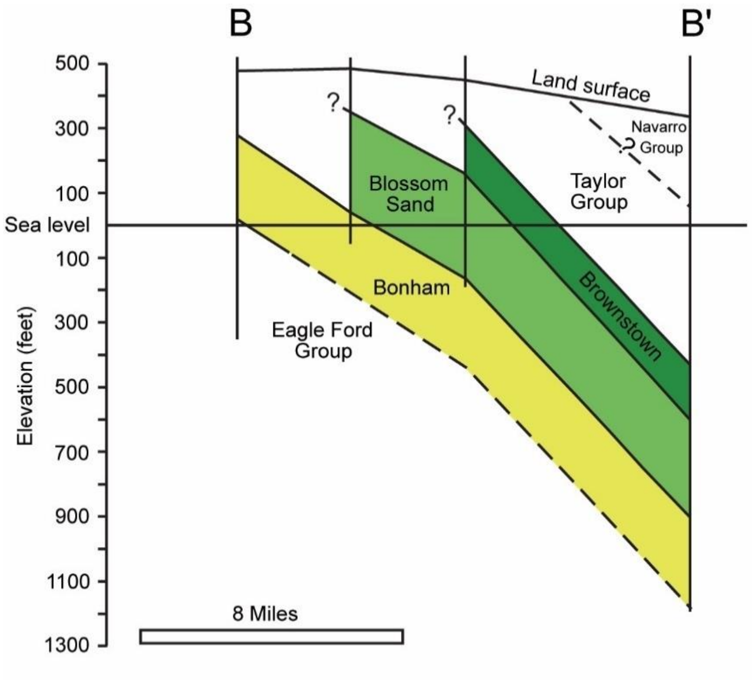


Figure 6-47. **North to south geologic cross-section across the Blossom Aquifer (modified from McLaurin, 1988).**

Flows to surface water and other aquifers

A summary of baseflow in the outcrop area of the Blossom Aquifer is reported in Table 6-31. Currently, there is no groundwater availability model for the Blossom Aquifer. The Blossom aquifer is separated from the underlying Trinity Aquifer by the shales of the Eagle Ford Group, which forms an effective aquitard between these systems (Kelley and others, 2014). No inter-aquifer flow is expected to occur between the Blossom Aquifer and the Trinity Aquifer or any other major or minor aquifer.

Table 6-31. **Summary of groundwater flow from the Blossom Aquifer to surface water, by county.**

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Bowie	15	3.3	1
Lamar	48	3.6	0.3
Red River	119	13.3	1.3
Total	**182**	**20**	**3**

Water quantity

Total storage in the Blossom Aquifer is estimated to be more than 7 million acre-feet. Recoverable storage is estimated to be between 25 and 75 percent of the total, about 1.7 million to 5.3 million acre-feet (Table 6-32).

Table 6-32. Total estimated recoverable storage in the Blossom Aquifer, by county, in acre-feet.

County	Total storage	25 percent of storage	75 percent of storage
Bowie	910,000	227,500	682,500
Lamar	970,000	242,500	727,500
Red River	5,200,000	1,300,000	3,900,000
Total	**7,080,000**	**1,770,000**	**5,310,000**

Water quality

The Blossom Aquifer yields water of usable quality to wells located mostly in outcrop areas. However, in part of Red River County, slightly saline water, with total dissolved solids less than 3,000 milligrams per liter, extends underground for about 6 miles south of the outcrop (Figure 6-48). Groundwater in the aquifer is generally soft, slightly alkaline, and, in some areas, high in sodium, bicarbonate, iron, and fluoride. The water has a high sodium adsorption ratio and ranks high on the residual sodium carbonate index, which makes it unsuitable for irrigation.

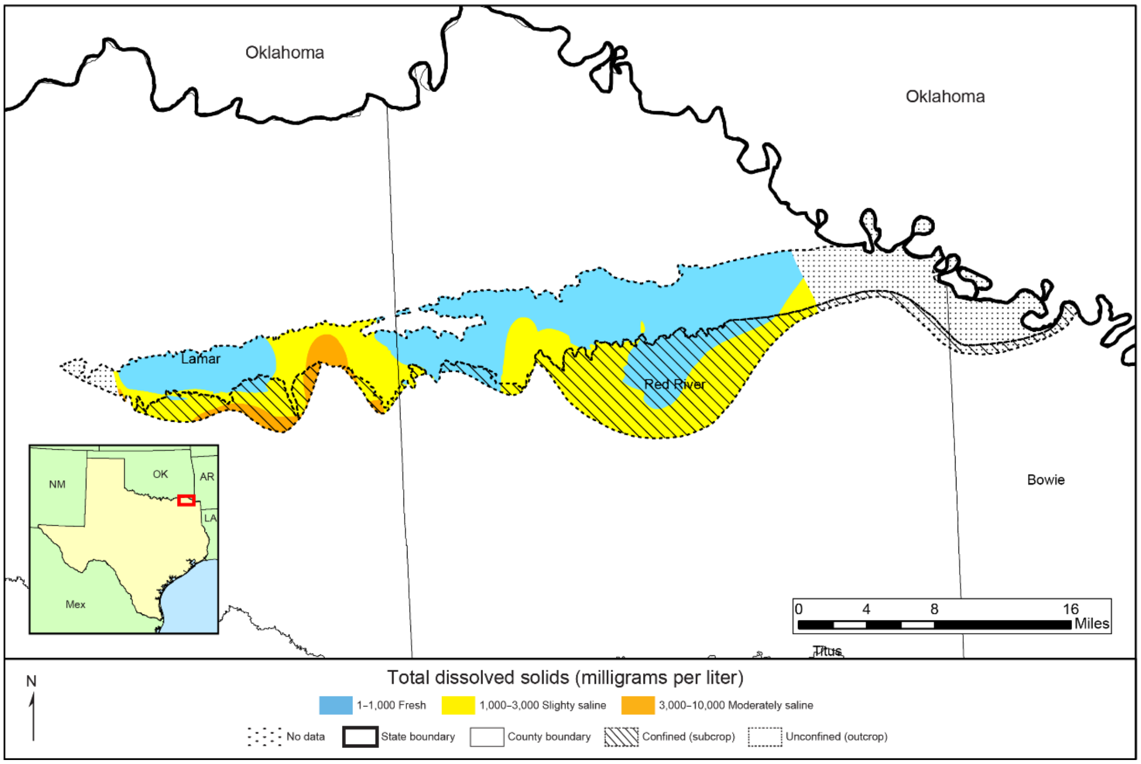


Figure 6-48. Total dissolved solids in the Blossom Aquifer.

6.12 Bone Spring-Victorio Peak Aquifer

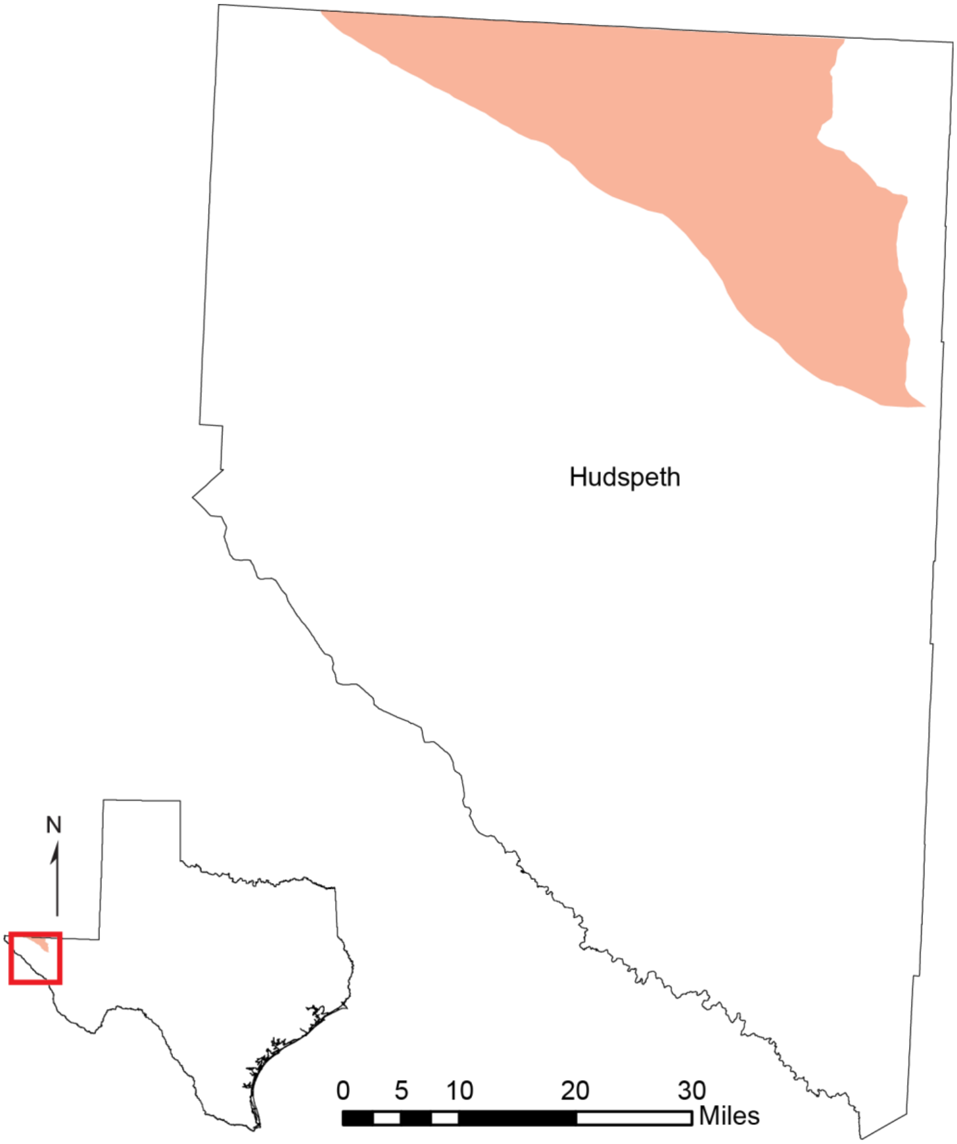


Figure 6-49. Extent of the Bone Spring-Victorio Peak Aquifer.

Aquifer characteristics

- Aquifer type: unconfined
- Area of aquifer: 713 square miles
- Proportion of aquifer within a groundwater conservation district: 100 percent
- Number of counties containing the aquifer: 1

Geology and hydrogeology

The Bone Spring-Victorio Peak Aquifer is a minor aquifer located in northern Hudspeth County and extending across the border into New Mexico (Figure 6-49). A cross-section of the aquifer is shown in Figure 6-50. Water occurs in dissolution features and along voids and fractures in two water-bearing limestone units, and the formation is locally very permeable. The estimated average effective recharge for the Bone Spring-Victorio Peak Aquifer in Hudspeth County is 4,035 acre-feet per year. Annual effective recharge is estimated at 5 percent of annual precipitation.

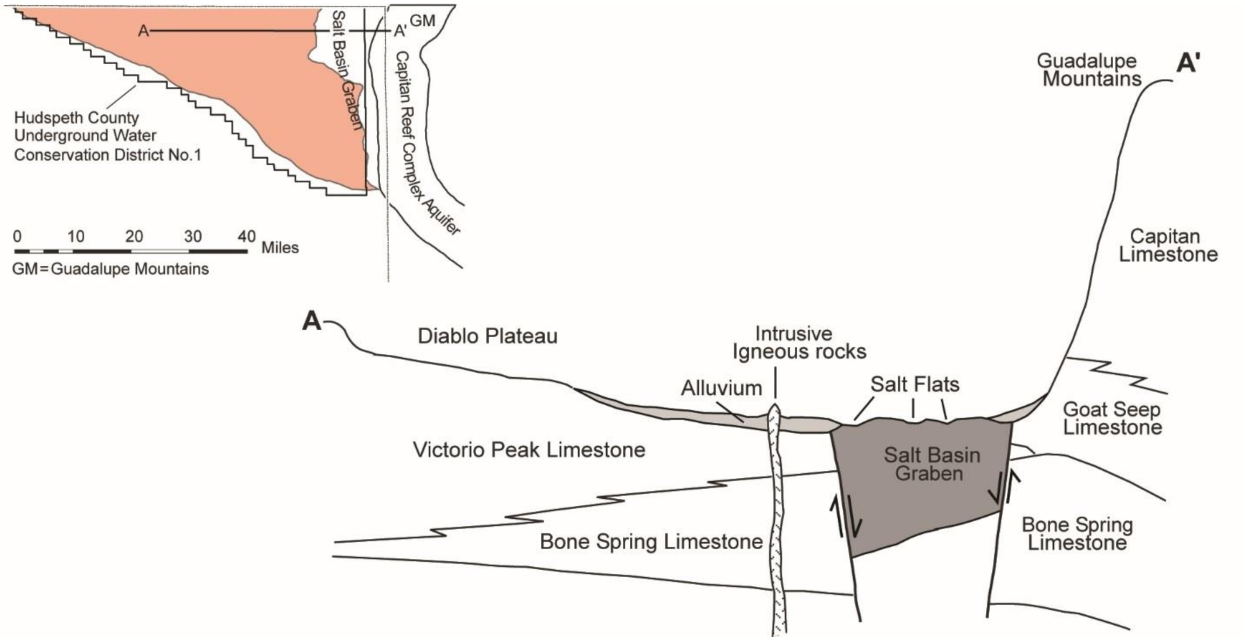


Figure 6-50. **Structural cross-section of the Bone Spring-Victorio Peak Aquifer in northeastern Hudspeth County (modified from Ashworth, 1995).**

Flows to surface water and other aquifers

The Bone Spring-Victorio Peak Aquifer naturally discharges to surface water. A summary of baseflow in the outcrop areas of the Bone Spring-Victorio Peak Aquifer is reported in Table 6-33

The Bone Spring-Victorio Peak Aquifer is not in direct contact with any other major or minor aquifers and consequently no inter-aquifer flow is expected to occur.

Table 6-33. **Summary of groundwater flow from the Bone Spring-Victorio Peak Aquifer to surface water, by county.**

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Hudspeth	713	9.3	4.5

Water quantity

Total storage in the Bone Spring-Victorio Peak Aquifer is estimated to be 3.7 million acre-feet. Recoverable storage is estimated to be between 25 and 75 percent of the total, about 925,000 and 2.7 million acre-feet (Table 6-34).

Table 6-34. **Total estimated recoverable storage in the Bone Spring-Victorio Peak Aquifer in Hudspeth County, in acre-feet.**

County	Total storage	25 percent of storage	75 percent of storage
Hudspeth	3,700,000	925,000	2,775,000
Total	**3,700,000**	**925,000**	**2,775,000**

Water quality

Water quality in the Bone Spring-Victorio Peak Aquifer is generally slightly saline, with total dissolved solids of 1,000 to 3,000 milligrams per liter. In the Dell Valley area, total dissolved solids increase to 3,000 to 10,000 milligrams per liter (Figure 6-51). Water quality in this area appears to be controlled by two mechanisms: 1) groundwater flowing through the aquifer system and dissolving minerals along its flow path and 2) irrigation water concentrated by evaporation percolating down through the soil zone.

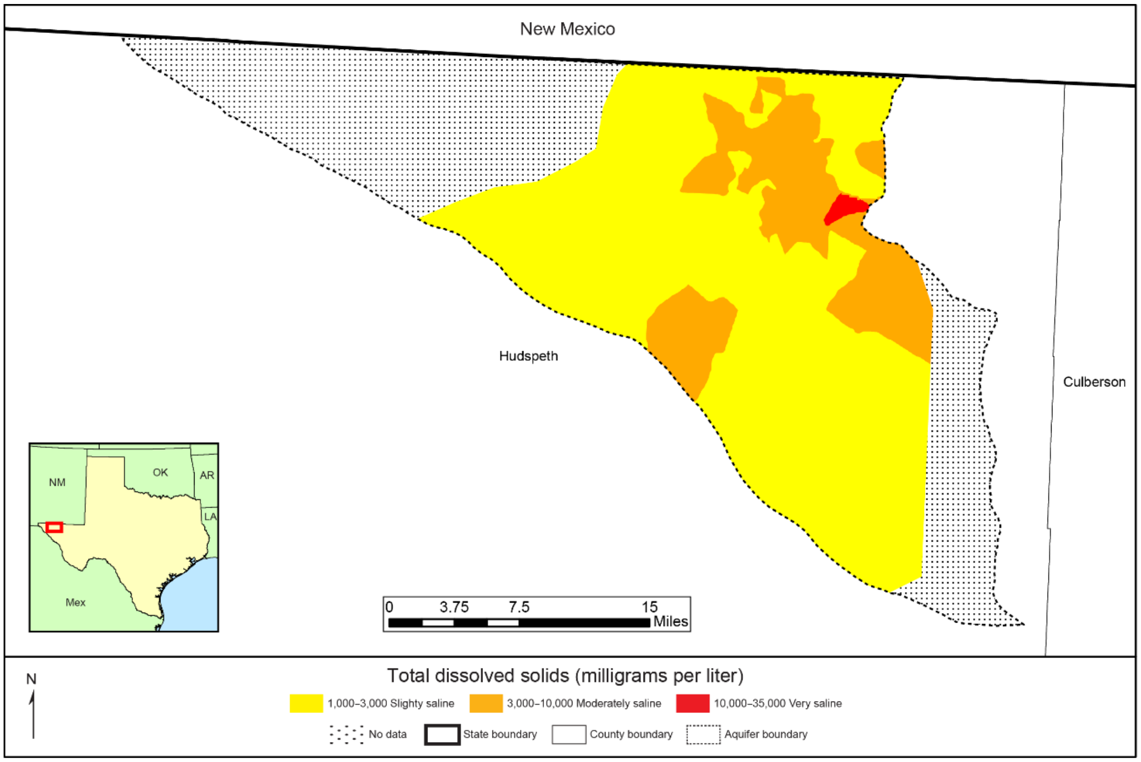


Figure 6-51. Total dissolved solids in the Bone Spring-Victorio Peak Aquifer.

6.13 Brazos River Alluvium Aquifer

Figure 6-52. Extent of the Brazos River Alluvium Aquifer.

Aquifer characteristics

- Aquifer type: unconfined
- Area of aquifer: 1,057 square miles
- Proportion of aquifer with groundwater conservation districts: 85 percent
- Number of counties containing the aquifer: 13

Geology and hydrogeology

The Brazos River Alluvium Aquifer is a minor aquifer found along the Brazos River in east central Texas. The aquifer is as much as 7 miles in width and extends along 350 river miles from southern Bosque County to eastern Fort Bend County (Figure 6-52). Groundwater is contained in alluvial floodplain and terrace deposits, although the latter is not an appreciable source of water. The floodplain alluvium consists of fine to coarse sand, gravel, silt, and clay. These deposits have a complex geometry, with beds or lenses of sand and gravel that pinch out or grade vertically into finer material. In general, finer sediments occur in the upper part of the aquifer while coarser material occurs in the lower part.

The thickness of the aquifer ranges from negligible to 168 feet, with an overall average of about 50 feet (Figure 6-53). The aquifer is unconfined and is mainly used for irrigation. The water table generally slopes toward the Brazos River, indicating that the river is a gaining stream in most places. Recharge to the aquifer occurs from rainfall onto the aquifer outcrop and subsequent downward leakage to the saturated zone. Discharge from the aquifer occurs through evapotranspiration, discharge to the river, and withdrawals from wells. The majority of wells yield from 250 to 500 gallons per minute, though some wells can yield as much as 1,000 gallons per minute. The mean hydraulic conductivity of the aquifer is estimated to be 241 feet per day (Shah and others, 2007). The specific yield is estimated to be 0.15 (Cronin and Wilson, 1967). No significant water-level declines have occurred in the aquifer to date.

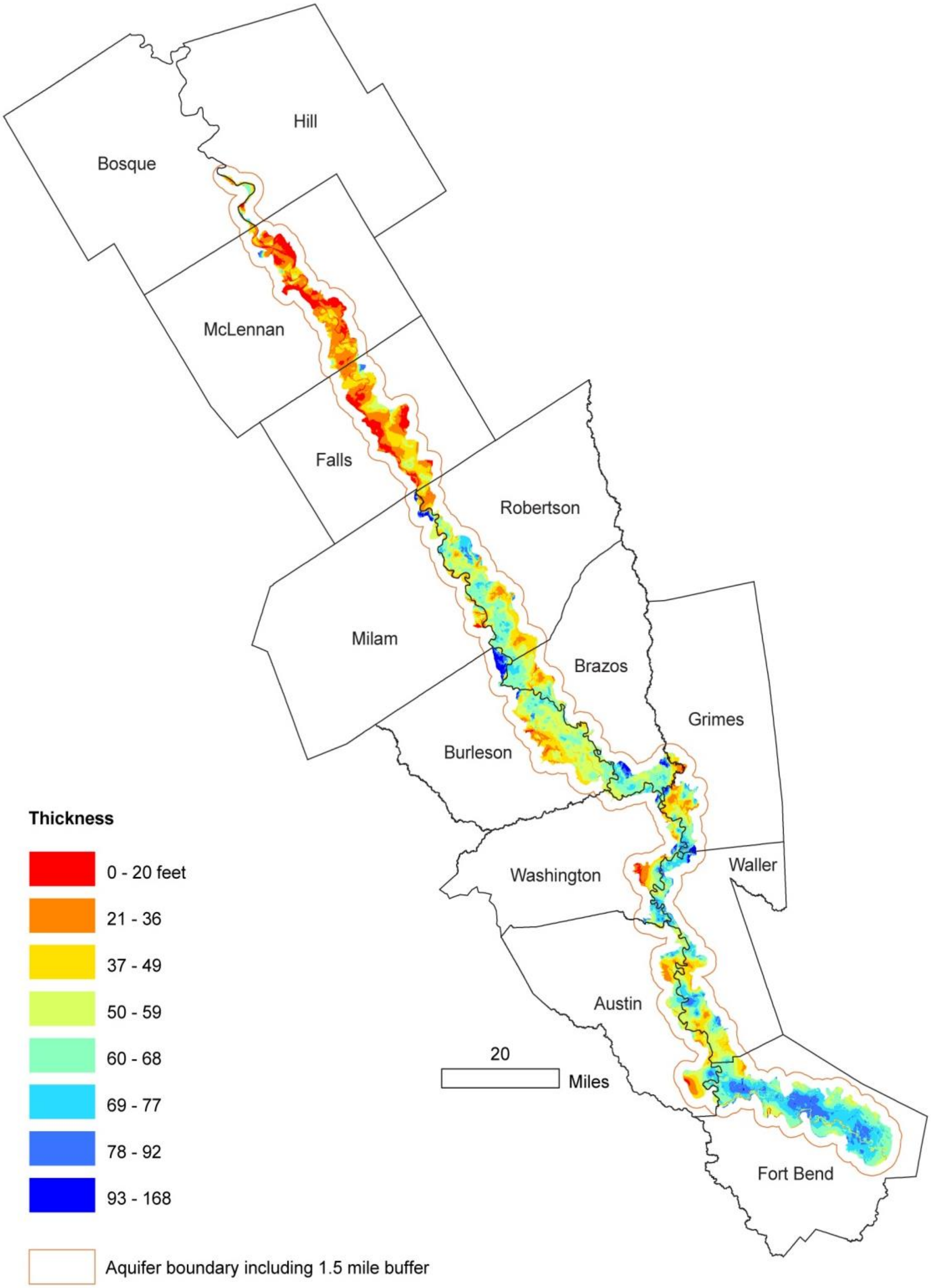


Figure 6-53. **Thickness of the Brazos River Alluvium Aquifer, Bosque County to Fort Bend County, Texas (from Shah and others, 2007).**

Flows to surface water and other aquifers

The Brazos River intersects the Brazos River Alluvium Aquifer, and there are several springs in the aquifer area. The aquifer also shows interaction with reservoirs and oxbow lakes in the area (Ewing and others, 2016). A summary of baseflow in the outcrop area of the Brazos River Alluvium Aquifer is reported in Table 6-35. Groundwater availability model analysis estimates a total flow to the Brazos River Alluvium Aquifer from the Carrizo-Wilcox Aquifer of 2,361 acre-feet per year (Table 6-36).

Table 6-35. Summary of groundwater flow from the Brazos River Alluvium Aquifer to surface water by county.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Austin	64	7.5	1.3
Bosque	6	0.2	0
Brazos	97	8.5	1.6
Burleson	129	9.1	1.6
Falls	113	5.3	0.7
Fort Bend	197	32.8	7.8
Grimes	43	3.1	0.4
Hill	4	0.1	0
McLennan	103	3.9	0.4
Milam	23	1.6	0.2
Robertson	132	9.3	1.1
Waller	98	11.1	2
Washington	47	3.5	0.7
Total	**1,056**	**96**	**18**

Table 6-36. Model estimates of inter-aquifer flows between the Brazos River Alluvium Aquifer and the Carrizo-Wilcox Aquifer.

Flow from	Flow to	Total flow (acre-feet per year)
Carrizo-Wilcox Aquifer	Brazos River Alluvium Aquifer	2,361

Water quantity

Total storage in the Brazos River Alluvium Aquifer is estimated to be more than 3 million acre-feet. Recoverable storage is estimated to be between 25 and 75 percent of the total, about 800,000 to 2.4 million acre-feet (Table 6-37).

Table 6-37. Total estimated recoverable storage in the Brazos River Alluvium Aquifer, by county, in acre-feet.

County	Total storage	25 percent of storage	75 percent of storage
Austin	220,000	55,000	165,000
Bosque	9,600	2,400	7,200
Brazos	290,000	72,500	217,500
Burleson	450,000	112,500	337,500
Falls	160,140	40,035	120,105
Fort Bend	1,010,000	252,500	757,500
Grimes	74,700	18,675	56,025
Hill	6,600	1,650	4,950
McLennan	90,000	22,500	67,500
Milam	36,700	9,175	27,525
Robertson	270,000	67,500	202,500
Waller	412,000	103,000	309,000
Washington	179,000	44,750	134,250
Total	**3,208,740**	**802,185**	**2,406,555**

Water quality

Water in the Brazos River Alluvium Aquifer is very hard and fresh to slightly saline, generally containing less than 1,000 milligrams per liter of total dissolved solids, but ranging to as much as 3,000 milligrams per liter in some wells (Figure 6-54). Only a small percentage of the aquifer area (1 to 2 percent) is at high risk of exceeding primary or secondary maximum contaminant levels. The northern aquifer extent is at risk of nitrate-N, gross alpha, barium, and arsenic primary maximum contaminant levels. High total dissolved solids dominate secondary maximum contaminant level exceedances (Reedy and others, 2011).

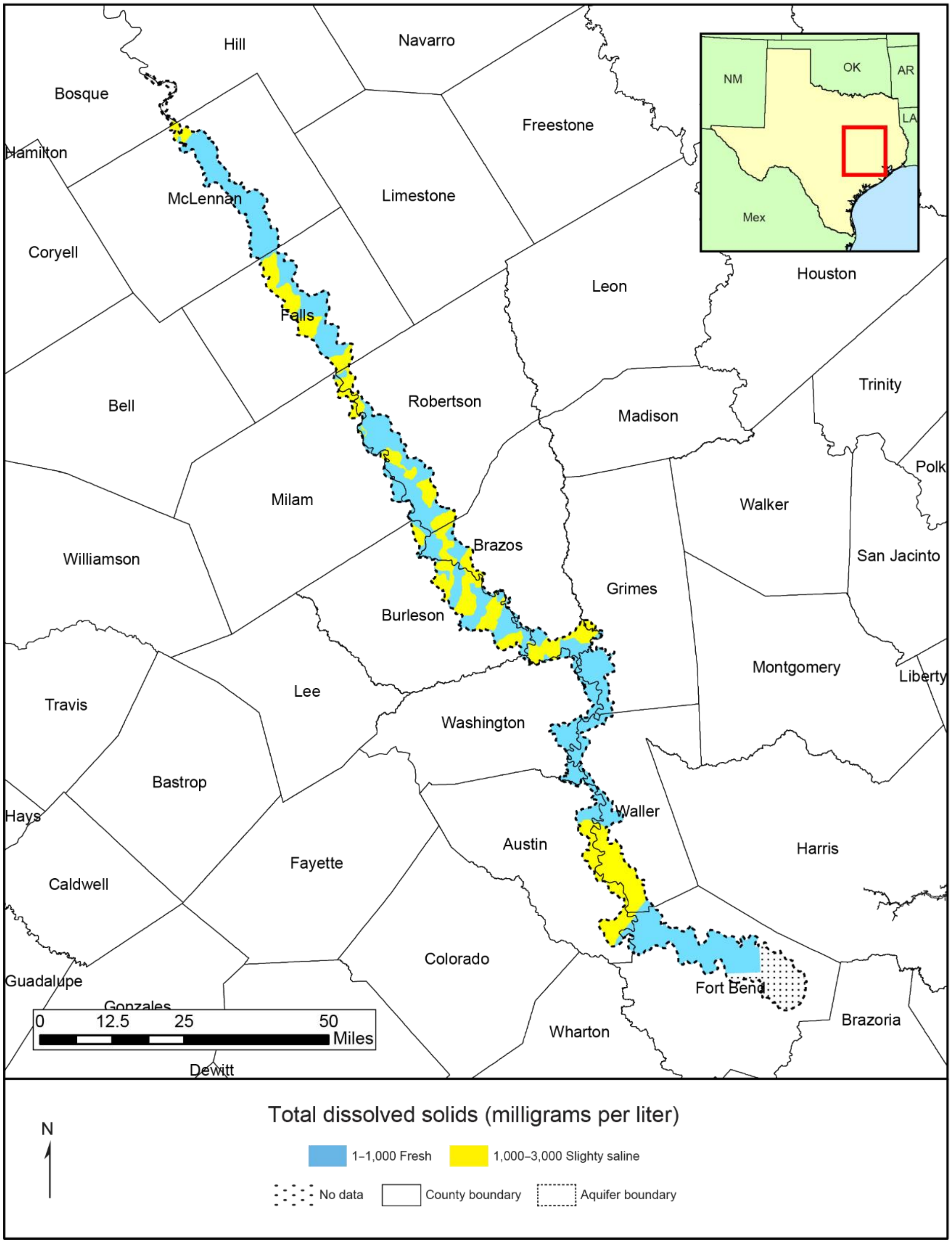


Figure 6-54. Total dissolved solids in the Brazos River Alluvium Aquifer

6.14 Capitan Reef Complex Aquifer

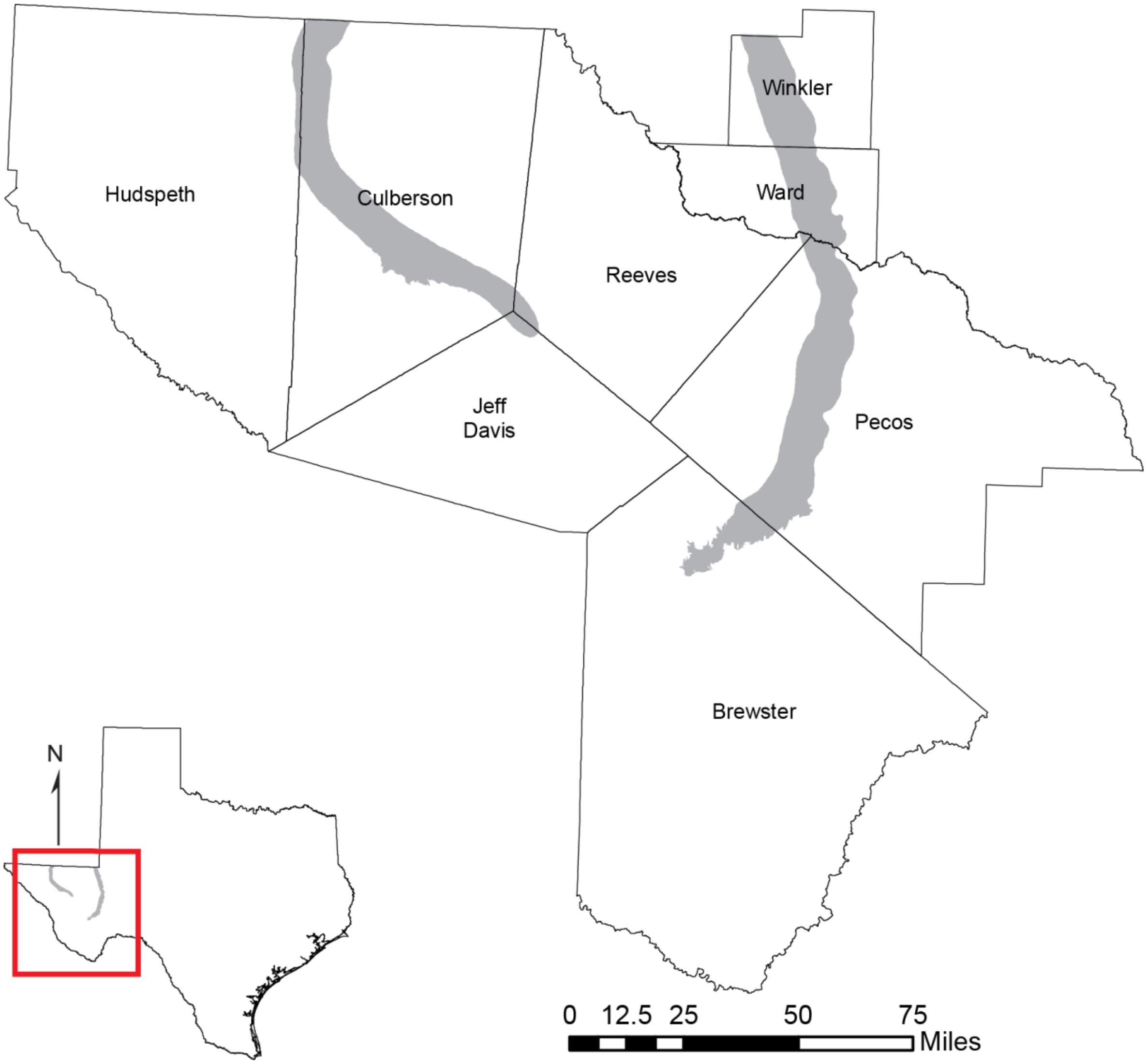


Figure 6-55. Extent of the Capitan Reef Complex Aquifer.

Aquifer characteristics

- Aquifer type: unconfined
- Area of aquifer: 1,850 square miles
- Proportion of aquifer with groundwater conservation districts: 62 percent
- Number of counties containing the aquifer: 8

Geology and hydrogeology

The Capitan Reef Complex Aquifer is a minor aquifer located in Culberson, Hudspeth, Jeff Davis, Brewster, Pecos, Reeves, Ward, and Winkler counties (Figure 6-55). It is exposed in mountain ranges of far west Texas; elsewhere it occurs in the subsurface. The aquifer is composed of as much as 2,360 feet of massive, cavernous dolomite and limestone. Water occurs in solution cavities and fractures that are unevenly distributed in the water-bearing dolomite and limestone formations (Figure 6-56, Figure 6-57, and Figure 6-58).

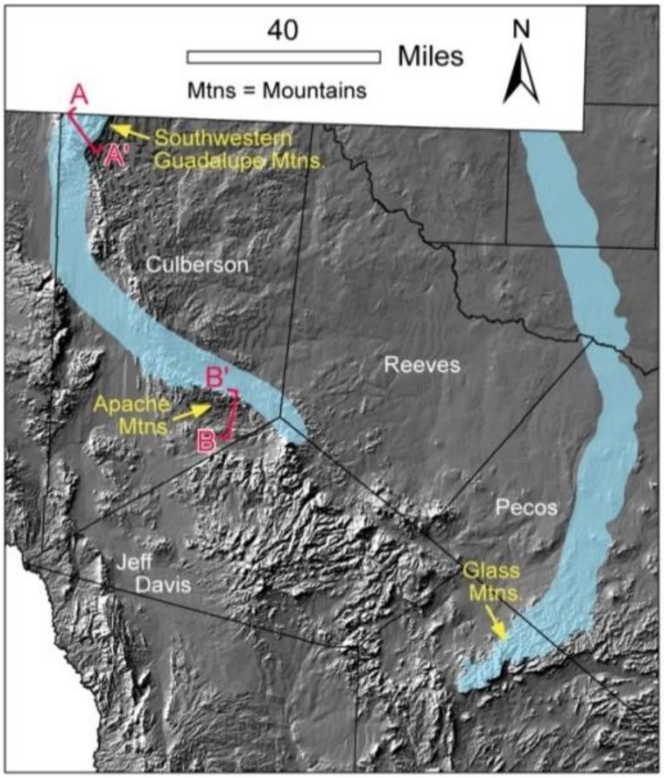


Figure 6-56. Cross-section locations overlaying a digital elevation model. Aquifer is highlighted in blue (modified from King, 1948; Hays, 1964; Tyrrell, 1969; and Pray, 1988).

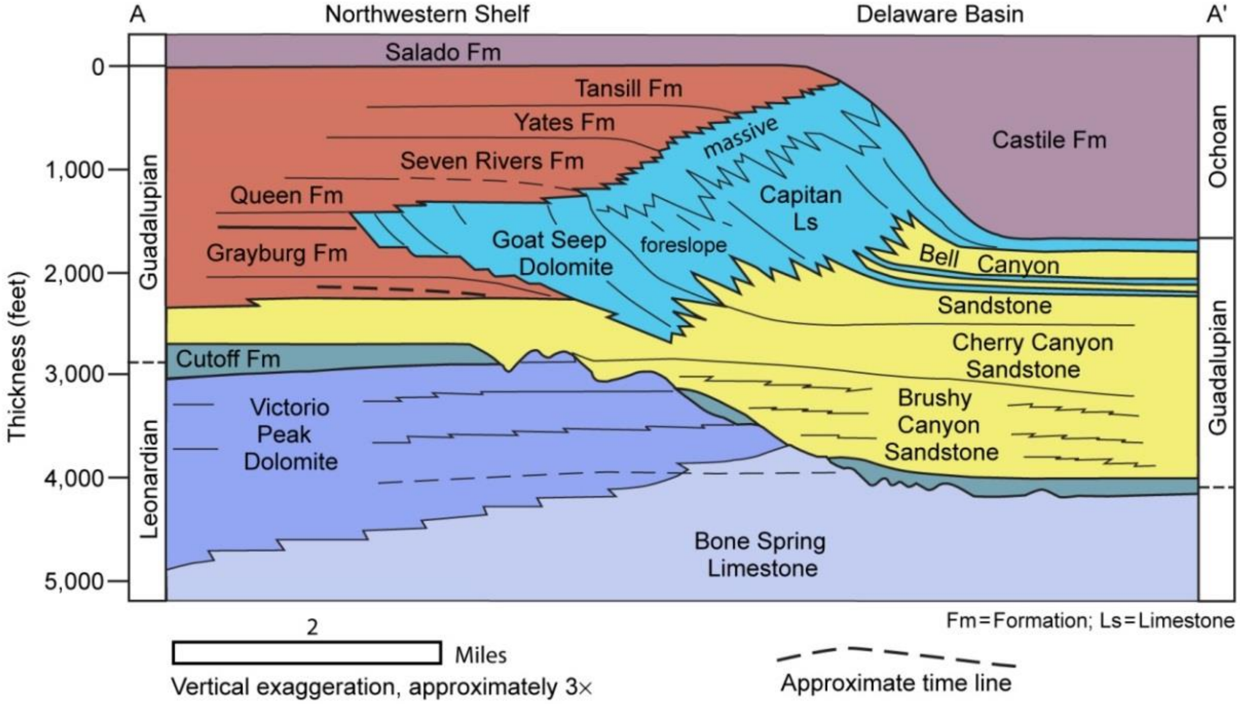
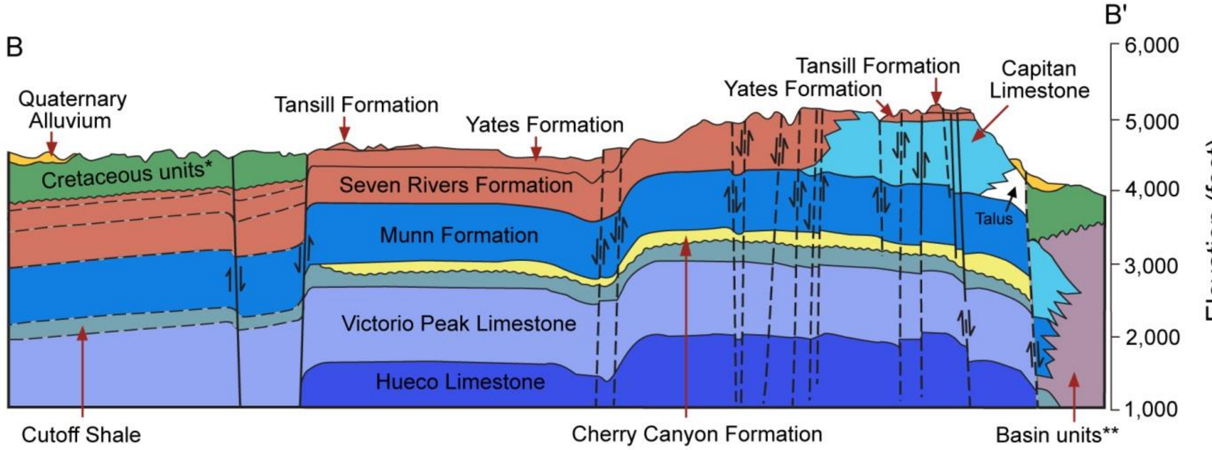


Figure 6-57. **Stratigraphic cross-section of the Capitan Reef Complex Aquifer from A to A′, shown in Figure 6-56 (modified from King, 1948; Hays, 1964; Tyrrell, 1969; and Pray, 1988).**



* includes Boracho Limestone (Levinson Member), Finlay Limestone, Cox Sandstone, Yearwood Formation
** includes Rustler Formation, Castile Limestone, Bell Canyon Sandstone, Cherry Canyon Sandstone

Figure 6-58. **Stratigraphic cross-section of the Capitan Reef Complex Aquifer from B to B′, shown in Figure 6-56 (modified from Wood, 1965).**

Flows to surface water and other aquifers

A portion of the Capitan Reef Complex Aquifer discharges to the Pecos River, and water from the Capitan Reef Complex Aquifer is thought to contribute to the baseflow of San Solomon Springs in Reeves County. A summary of baseflow in the outcrop areas of the Capitan Reef Complex Aquifer is reported in Table 6-38. The Capitan Reef Complex Aquifer is separated from the overlying Rustler and Dockum aquifers by the Salado and Castille Formations, which form an effective aquitard preventing groundwater flow. Groundwater availability model analysis does not estimate any inter-aquifer flow between the Capitan Reef Complex Aquifer and other major and minor aquifers.

Table 6-38. Summary of groundwater flow from the Capitan Reef Complex Aquifer to surface water.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Brewster	90	0.3	0.1
Culberson	66	0.5	0.2
Hudspeth	4	0	0
Pecos	27	0.1	0.1
Total	**187**	**1**	**0**

Water quantity

Total storage in the Capitan Reef Complex Aquifer is estimated to be more than 55 million acre-feet. Recoverable storage is estimated to be between 25 and 75 percent of the total, about 13.7 million to 41.3 million acre-feet (Table 6-39).

Table 6-39. Total estimated recoverable storage in the Capitan Reef Complex Aquifer, in acre-feet.

County	Total storage	25 percent of storage	75 percent of storage
Brewster	2,500,000	625,000	1,875,000
Culberson	21,000,000	5,250,000	15,750,000
Hudspeth	1,100,000	275,000	825,000
Jeff Davis	760,000	190,000	570,000
Pecos	16,800,000	4,200,000	12,600,000
Reeves	930,000	232,500	697,500
Ward	5,900,000	1,475,000	4,425,000
Winkler	6,100,000	1,525,000	4,575,000
Total	**55,090,000**	**13,772,500**	**41,317,500**

Water quality

Overall, the aquifer contains water of marginal quality, yielding small to large quantities of slightly saline to saline groundwater containing 1,000 to greater than 5,000 milligrams per liter of total dissolved solids. Water of the freshest quality, with total dissolved solids between 300 and 1,000 milligrams per liter, is present in the west near areas of recharge where the reef rock is exposed in several mountain ranges. Figure 6-59 shows total dissolved solids in the Capitan Reef Complex Aquifer.

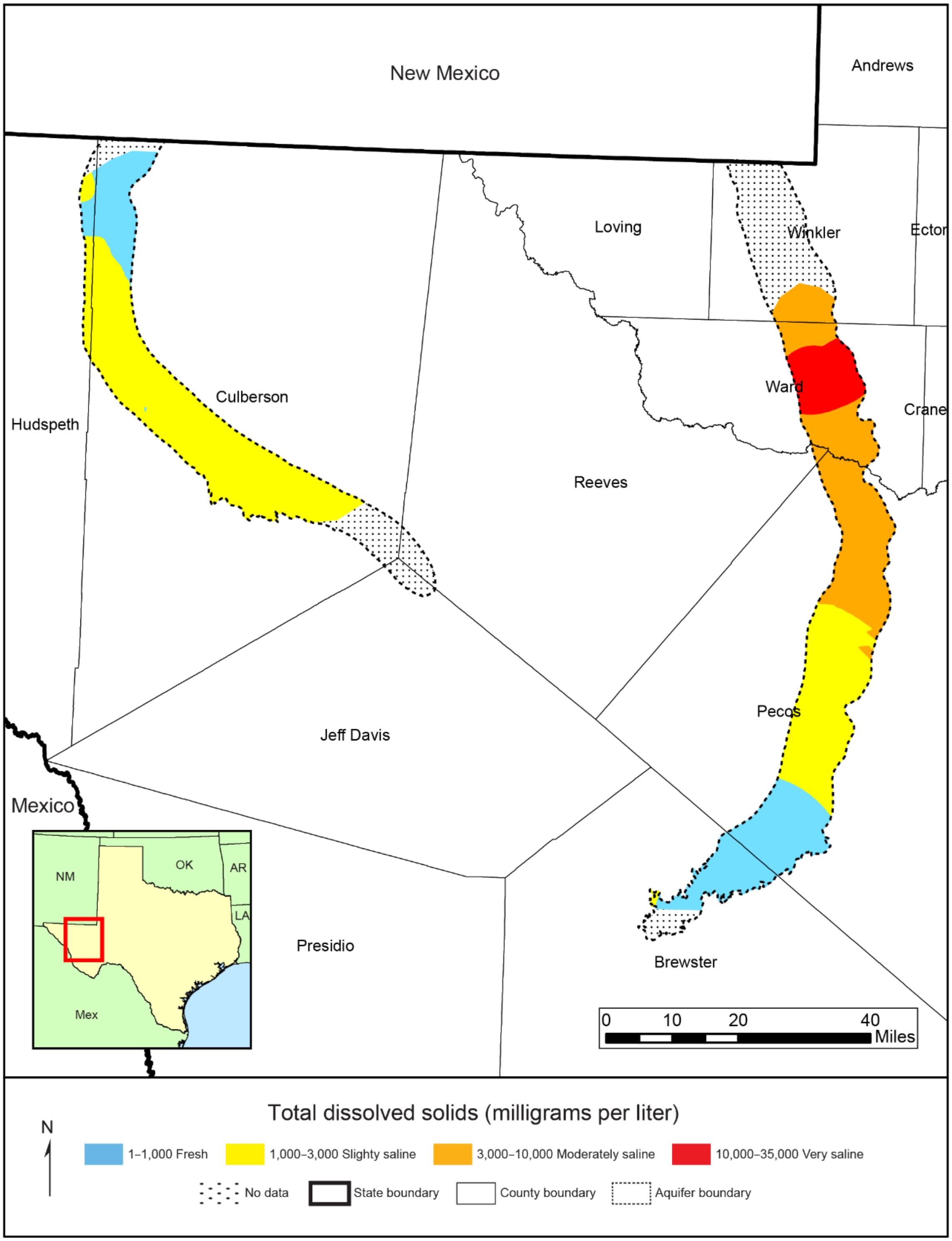


Figure 6-59. Total dissolved solids in the Capitan Reef Complex Aquifer.

6.15 Dockum Aquifer

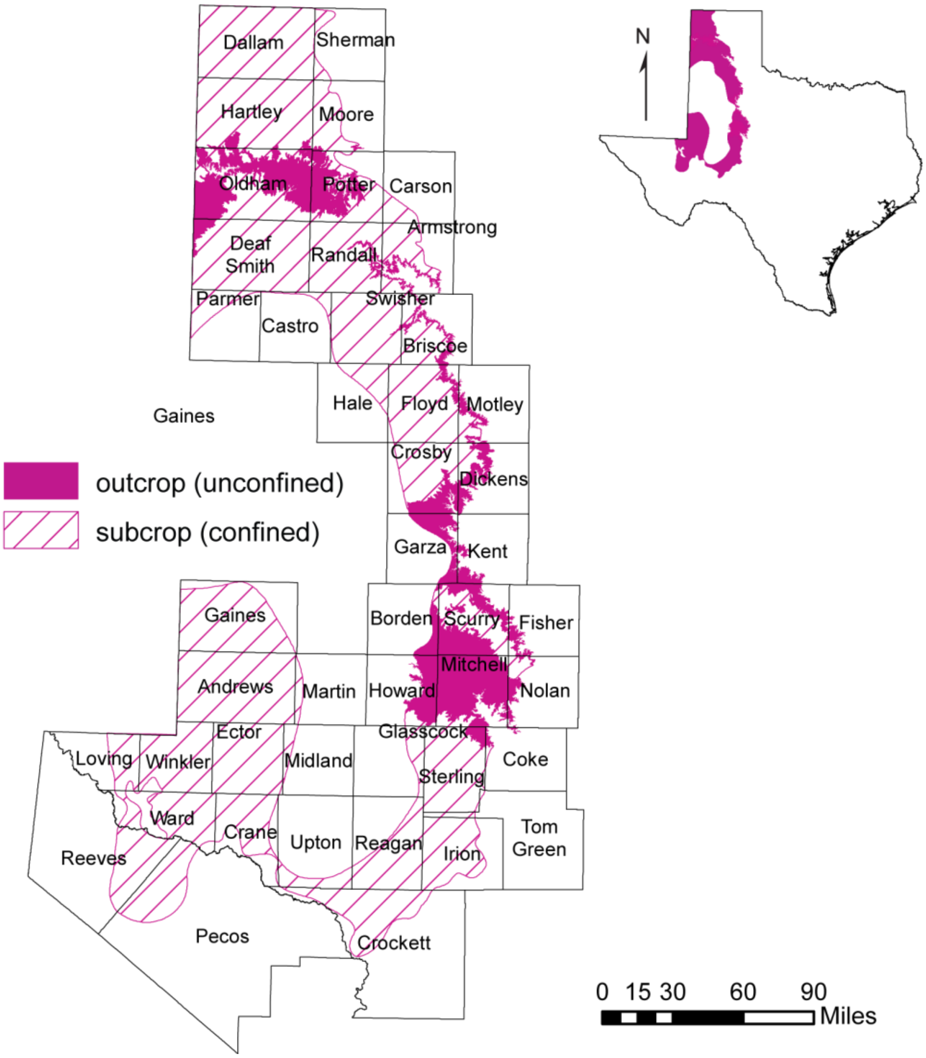


Figure 6-60. Extent of the Dockum Aquifer.

Aquifer characteristics

- Aquifer type: confined and unconfined
- Area of outcrop: 3,525 square miles
- Area in subsurface: 22,030 square miles
- Proportion of aquifer with groundwater conservation districts: 55 percent
- Number of counties containing the aquifer: 46

Geology and hydrogeology

The Dockum Aquifer is a minor aquifer found in the northwestern part of the state (Figure 6-60). It is defined stratigraphically by the Dockum Group, which is composed of sandstones, conglomerates, mudstones, and siltstones.

The Dockum Aquifer is overlain by the Ogallala Aquifer except in the outcrop areas along the Canadian and Colorado Rivers where the Ogallala has been eroded away, as shown in Figure 6-61. Permian red-bed shales underlie the Dockum Aquifer, forming a no-flow lower boundary. Portions of the Dockum Aquifer are in direct hydraulic communication with the Ogallala Aquifer, and it is treated as part of the High Plains Aquifer System for purposes of groundwater availability modeling (Deeds and others, 2015).

Groundwater in sandstone and conglomerate units is recoverable, with the highest yields typically coming from the coarsest grained deposits located at the base of the Dockum Group; these water-bearing sandstones are locally referred to as the Santa Rosa Aquifer. The mean hydraulic conductivity is 0.2 feet per day for the upper Dockum Aquifer and 0.4 feet per day for the lower Dockum Aquifer (Ewing and others, 2008) but can range as high as 22 feet per day in some areas (Deeds and others, 2015).

Recharge to the outcrop area of the Dockum Aquifer is believed to have increased over the last century from 0.15 inches per year to 0.58 inches per year as a result of development and accompanying land-use changes. Because the outcrop area is located downgradient from the confined portion of the aquifer, the recharge flows toward the Canadian or Colorado Rivers and their tributaries, with little or no recharge entering the confined area. The confined portions of the Dockum are believed to have been recharged by precipitation on higher elevation outcrops in New Mexico during the Pleistocene, which have since been eroded, cutting off recharge (Ewing and others, 2008).

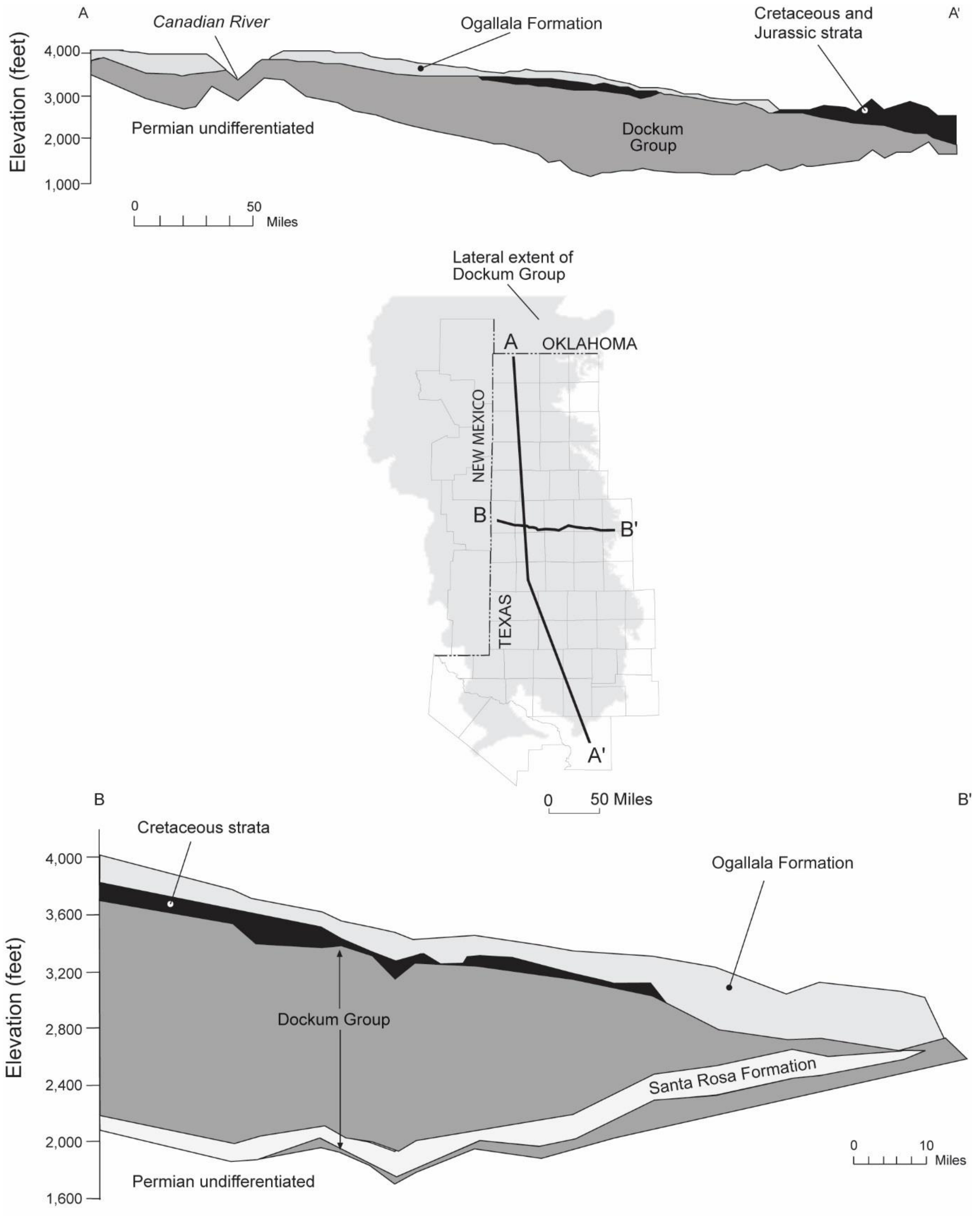


Figure 6-61. **Structural cross-sections across the Dockum Aquifer (modifed from Bradley and Kalaswad, 2003).**

Flows to surface water and other aquifers

Groundwater in the Dockum Aquifer generally flows to the southeast or east-southeast. Locally, groundwater diverts from this general direction toward springs and the Canadian, Brazos, and Colorado River drainage basins (Deeds and others, 2015). Springs occur in areas where Dockum Aquifer sediments intersect the water table. Brune (1981) described springs issuing from the Dockum Aquifer along the Pecos River Valley. Many of these springs are now dry or have lower flows than they did in the past (Bradley and Kalaswad, 2003).

Diffuse discharge from the Dockum Aquifer contributes to the baseflow of streams and rivers crossing its outcrop area. Analysis of U.S. Geological Survey baseflow index and hydrological landscape unit data give an estimated average surface discharge from the Dockum Aquifer of 18.2 cubic feet per second and a median discharge of 5.6 cubic feet per second. Table 6-40 shows a summary of baseflow in the outcrop areas of the Dockum Aquifer.

In some areas the water level in the Dockum Aquifer is higher than that in the Ogallala Aquifer, creating the potential for upward flow; chemical and isotopic data also support localized upward flow from the Dockum Group to the Ogallala Aquifer (Deeds and others, 2015). Table 6-41 shows groundwater availability model estimates of total flow and average annual flow between the Dockum Aquifer and other aquifers. Because of the large regional extent of the aquifer, some flow is estimated both from the Dockum Aquifer to the Ogallala Aquifer and from the Ogallala Aquifer to the Dockum Aquifer.

Table 6-40. Summary of groundwater flow from the Dockum Aquifer to surface water, by county

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Armstrong	52	0.1	0.1
Borden	91	0.3	0
Briscoe	58	0.2	0.1
Coke	14	0	0
Crosby	158	0.9	0.8
Deaf Smith	57	0.7	0.2
Dickens	144	1.1	0.6
Fisher	47	0.3	0
Floyd	36	0.3	0.2
Garza	206	0.4	0.1

Table 6-40 (continued). Summary of groundwater flow from the Dockum Aquifer to surface water, by county

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Hartley	38	0.1	0.1
Howard	250	1.1	0.2
Kent	72	0.4	0
Martin	25	0.1	0
Mitchell	725	3.4	0.2
Moore	7	0	0
Motley	53	0.6	0.4
Nolan	59	0.3	0
Oldham	735	4.8	1.8
Potter	294	1.3	0.4
Randall	22	0	0
Scurry	360	1.8	0.1
Sterling	46	0.1	0
Swisher	1	0	0
Total	**3,550**	**18**	**5**

Table 6-41. Model estimates of inter-aquifer flows between the Dockum Aquifer and other major and minor aquifers.

Flow from	Flow to	Total flow (acre-feet per year)
Dockum Aquifer	Edwards-Trinity (Plateau) Aquifer	37,509
Dockum Aquifer	Ogallala Aquifer	2,241
Dockum Aquifer	Rita Blanca Aquifer	115
Edwards-Trinity (Plateau) Aquifer	Dockum Aquifer	2,948
Ogallala Aquifer	Dockum Aquifer	27,497
Rita Blanca Aquifer	Dockum Aquifer	83
Rustler Aquifer	Dockum Aquifer	1

Water quantity

Total storage in the Dockum Aquifer is estimated to be over 1.5 billion acre-feet. Recoverable storage is estimated to be between 25 and 75 percent of the total, about 373.5 million to 1.1 billion acre-feet (Table 6-42).

Table 6-42. Total estimated recoverable storage in the Dockum Aquifer, by county, in acre-feet.

County	Total storage	25 percent of storage	75 percent of storage
Andrews	220,000,000	55,000,000	165,000,000
Armstrong	7,000,000	1,750,000	5,250,000
Borden	7,600,000	1,900,000	5,700,000
Briscoe	18,000,000	4,500,000	13,500,000
Carson	1,900,000	475,000	1,425,000
Castro	7,000,000	1,750,000	5,250,000
Coke	520,000	130,000	390,000
Crane	30,000,000	7,500,000	22,500,000
Crockett	14,000,000	3,500,000	10,500,000
Crosby	30,000,000	7,500,000	22,500,000
Dallam	80,000,000	20,000,000	60,000,000
Deaf Smith	130,000,000	32,500,000	97,500,000
Dickens	3,400,000	850,000	2,550,000
Ector	100,000,000	25,000,000	75,000,000
Fisher	1,300,000	325,000	975,000
Floyd	40,000,000	10,000,000	30,000,000
Gaines	200,000,000	50,000,000	150,000,000
Garza	4,900,000	1,225,000	3,675,000
Glasscock	11,000,000	2,750,000	8,250,000
Hale	16,000,000	4,000,000	12,000,000
Hartley	96,000,000	24,000,000	72,000,000
Howard	22,000,000	5,500,000	16,500,000
Irion	9,100,000	2,275,000	6,825,000
Kent	1,400,000	350,000	1,050,000
Loving	4,500,000	1,125,000	3,375,000
Martin	11,000,000	2,750,000	8,250,000
Midland	10,000,000	2,500,000	7,500,000
Mitchell	27,000,000	6,750,000	20,250,000
Moore	7,400,000	1,850,000	5,550,000
Motley	1,800,000	450,000	1,350,000

Table 6-42 (continued). Total estimated recoverable storage in the Dockum Aquifer, by county, in acre-feet.

County	Total storage	25 percent of storage	75 percent of storage
Nolan	2,100,000	525,000	1,575,000
Oldham	43,000,000	10,750,000	32,250,000
Parmer	30,000,000	7,500,000	22,500,000
Pecos	19,500,000	4,875,000	14,625,000
Potter	10,000,000	2,500,000	7,500,000
Randall	46,000,000	11,500,000	34,500,000
Reagan	17,000,000	4,250,000	12,750,000
Reeves	12,000,000	3,000,000	9,000,000
Scurry	32,000,000	8,000,000	24,000,000
Sherman	540,000	135,000	405,000
Sterling	33,000,000	8,250,000	24,750,000
Swisher	66,000,000	16,500,000	49,500,000
Tom Green	1,100,000	275,000	825,000
Upton	9,300,000	2,325,000	6,975,000
Ward	18,000,000	4,500,000	13,500,000
Winkler	42,000,000	10,500,000	31,500,000
Total	**1,494,360,000**	**373,590,000**	**1,120,770,000**

Water quality

Water quality in the Dockum Aquifer is generally poor and very hard, with freshwater in outcrop areas in the east and brine in the western subsurface portions of the aquifer. The distribution of total dissolved solids in the Dockum Aquifer, based on data from over 1,000 wells completed in the aquifer, is shown in Figure 6-62.

Naturally occurring radioactivity from uranium present within the aquifer has resulted in gross alpha radiation in excess of the state's primary drinking water standard in about 25 percent of Dockum Aquifer wells. Radium-226 and -228 also occur in amounts above acceptable standards. Nitrate is present at concentrations exceeding primary drinking water standards in about 10 percent of the wells, mostly in the outcrop areas, where it is associated with agricultural operations. Dockum Aquifer groundwater exceeds secondary drinking water standards for chloride, fluoride, iron, sulfate, and total dissolved solids in about one-third of the wells tested, primarily as a result of the evaporite minerals present in the Dockum Group and underlying formations of the Permian Basin (Reedy and others, 2011).

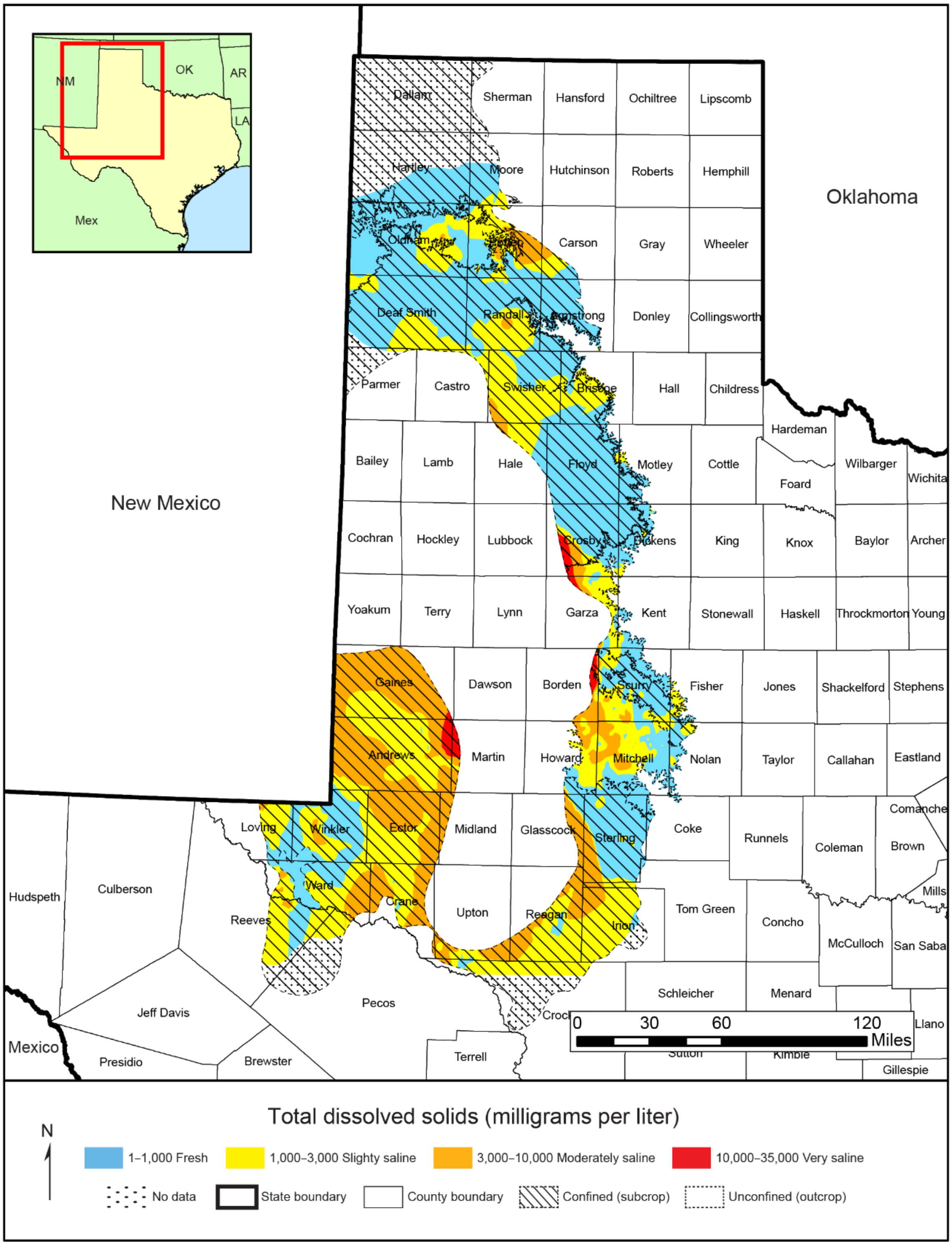


Figure 6-62. Total dissolved solids in the Dockum Aquifer.

6.16 Edwards-Trinity (High Plains) Aquifer

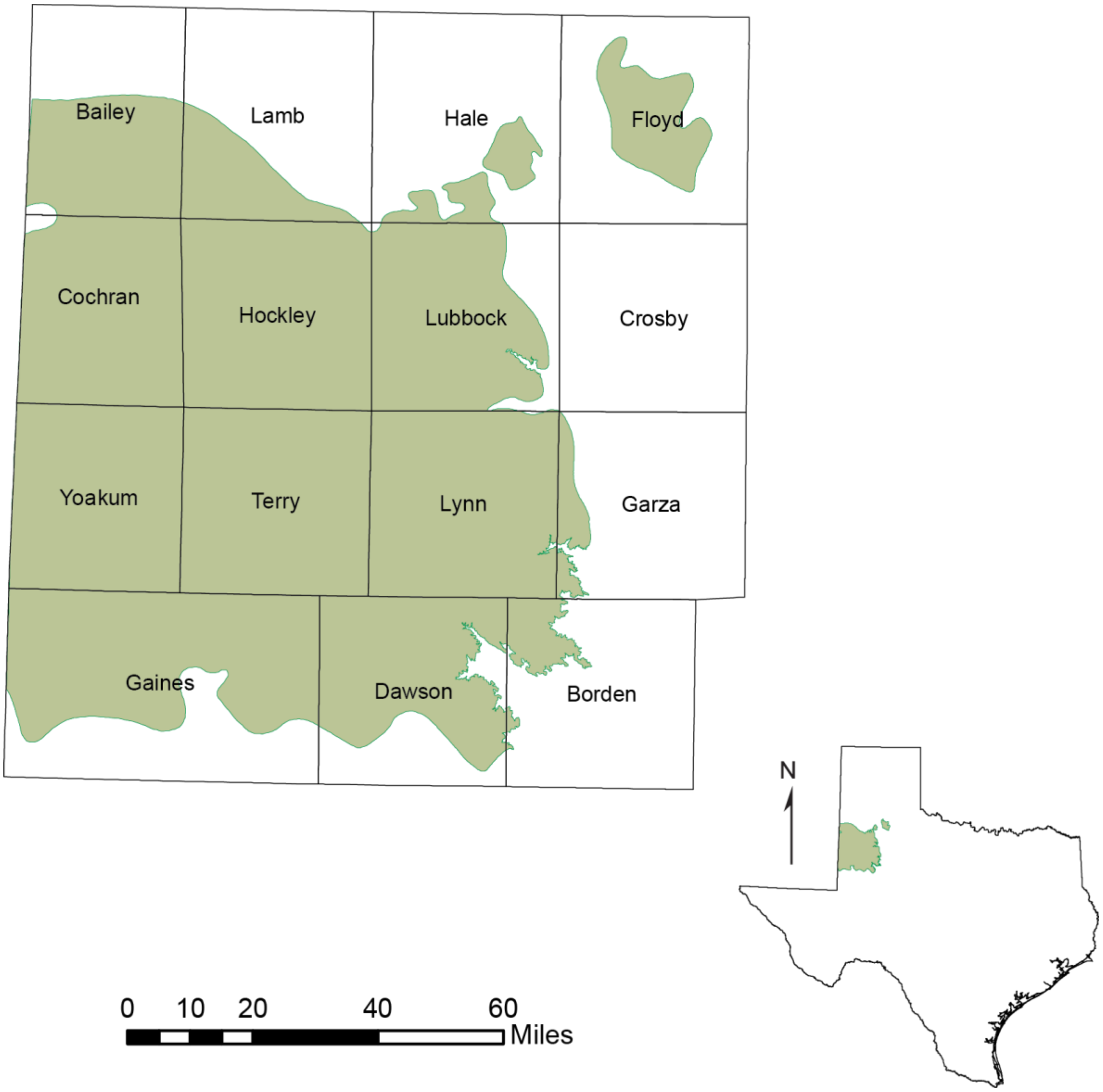


Figure 6-63. Extent of the Edwards-Trinity High Plains Aquifer.

Aquifer characteristics

- Aquifer type: mostly confined
- Area of aquifer: 7,912 square miles
- Proportion of aquifer with groundwater conservation districts: 98 percent
- Number of counties containing the aquifer: 15

Geology and hydrogeology

The Edwards-Trinity (High Plains) Aquifer is a minor aquifer that underlies about 9,000 square miles of the Ogallala Aquifer in western Texas and eastern New Mexico (Figure 6-63). Its water-producing units include sandstone and limestone. Freshwater saturated thickness in the aquifer averages 126 feet. Regional groundwater flow in the aquifer is to the southeast, but locally, flow is determined by the presence of paleo-channels containing Ogallala Formation sediments that are incised into the Cretaceous limestone forming the Edwards-Trinity (High Plains) Aquifer. Recharge to the aquifer is primarily due to downward leakage from the younger Ogallala Aquifer. The greatest amounts of recharge most likely occur where low-permeability clay layers, which lie between the Edwards-Trinity (High Plains) and Ogallala aquifers, are missing, thin, or relatively permeable (Figure 6-64). Groundwater in the Edwards-Trinity (High Plains) Aquifer generally is confined, although there are small areas where the aquifer is unconfined. Blandford and others (2008) modeled the specific storage of the confined portion of the aquifer with a value of 3×10^{-6} based on results for similar aquifers.

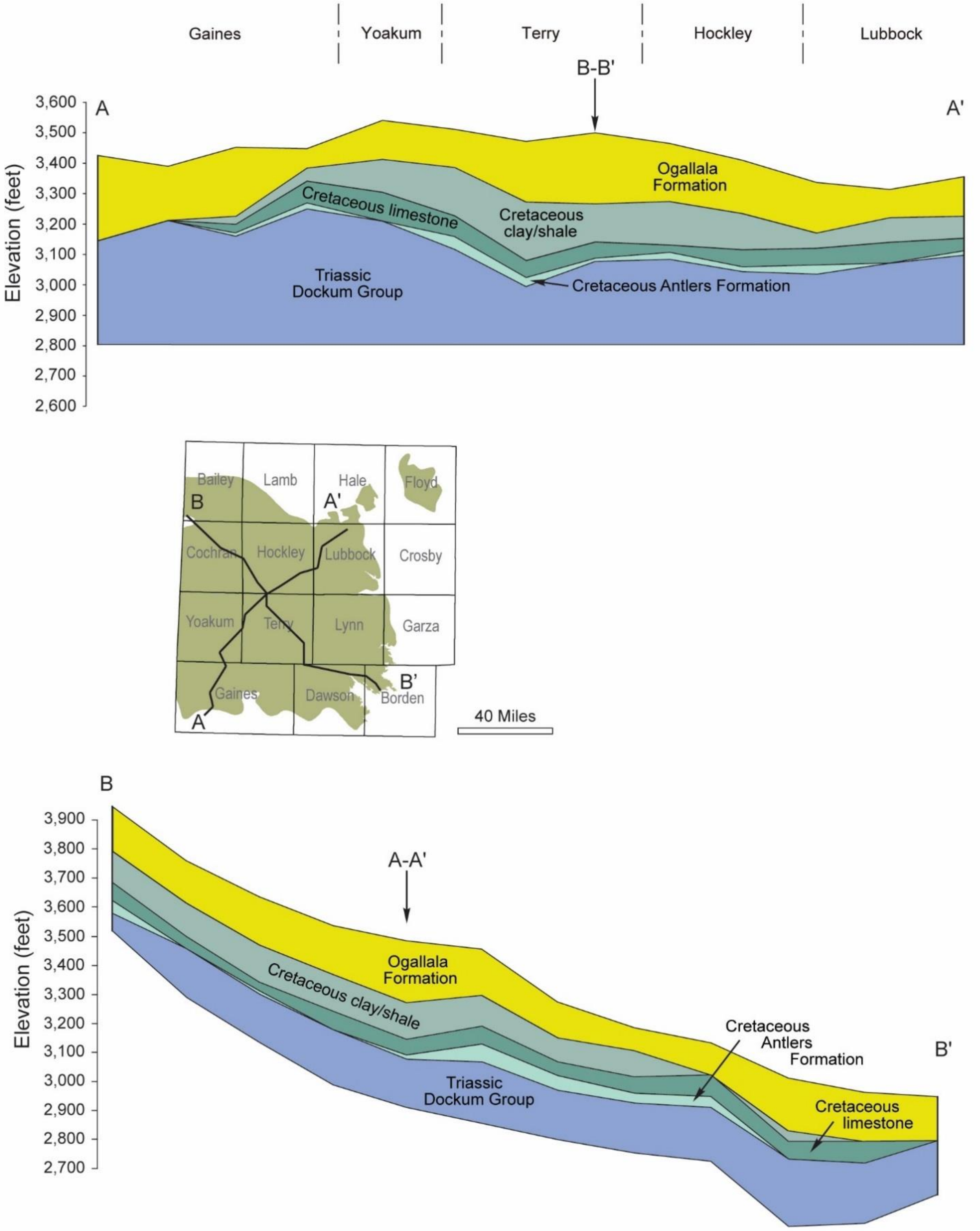


Figure 6-64. **Geologic cross-section across the Edwards-Trinity (High Plains) Aquifer (modified from Blandford and others, 2008).**

Flows to surface water and other aquifers

Table 6-43 shows a summary of baseflow in the Edwards-Trinity (High Plains) Aquifer. Discharge from the Edwards-Trinity (High Plains) Aquifer occurs at springs and seeps along the eastern caprock escarpment and at a number of large salt lakes west of the escarpment (Blandford and others, 2008). Table 6-44 shows groundwater availability model estimates of total flow and average annual flow between the Edwards-Trinity (High Plains) Aquifer and other aquifers. The predominant direction of flow is downward from the Ogallala Aquifer into the Edwards-Trinity (High Plains) Aquifer, although in some areas there is upward leakage to the Ogallala Aquifer as a result of water table drawdown in that aquifer.

Table 6-43. Summary of groundwater flow from the Edwards-Trinity (High Plains) Aquifer to surface water.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Borden	17	0.1	0
Dawson	14	0	0.1
Garza	3	0	0
Lynn	2	0	0
Total	**36**	**0.1**	**0.1**

Table 6-44. Model estimates of inter-aquifer flows between the Edwards-Trinity (High Plains) Aquifer and other major and minor aquifers.

Flow from	Flow to	Total flow (acre-feet per year)
Edwards-Trinity (High Plains) Aquifer	Ogallala Aquifer	5,544
Ogallala Aquifer	Edwards-Trinity (High Plains) Aquifer	13,812

Water quantity

Total storage in the Edwards-Trinity (High Plains) Aquifer is estimated to be more than 23 million acre-feet. Recoverable storage is estimated to be between 25 and 75 percent of the total, or about 5.9 million to 17.7 billion acre-feet (Table 6-45).

Table 6-45. Total estimated recoverable storage in the Edwards-Trinity (High Plains) Aquifer, by county, in acre-feet.

County	Total storage	25 percent of storage	75 percent of storage
Bailey	690,000	172,500	517,500
Borden	1,600,000	400,000	1,200,000
Cochran	1,700,000	425,000	1,275,000
Dawson	1,000,000	250,000	750,000
Floyd	730,000	182,500	547,500
Gaines	3,100,000	775,000	2,325,000
Garza	120,000	30,000	90,000
Hale	870,000	217,500	652,500
Hockley	2,200,000	550,000	1,650,000
Lamb	500,000	125,000	375,000
Lubbock	2,000,000	500,000	1,500,000
Lynn	3,400,000	850,000	2,550,000
Terry	3,300,000	825,000	2,475,000
Yoakum	2,500,000	625,000	1,875,000
Total	**23,710,000**	**5,927,500**	**17,782,500**

Water quality

Groundwater in the Edwards-Trinity (High Plains) Aquifer typically contains more total dissolved solids than does the overlying Ogallala Aquifer. It generally is slightly saline, with total dissolved solids ranging from 1,000 to 2,000 milligrams per liter, but can range from 400 to more than 3,000 milligrams per liter. Areas with higher total dissolved solids concentrations are primarily located in the south central region of the aquifer (Figure 6-65). Groundwater is poorest in quality where the aquifer is overlain by saline lakes or the gypsum-rich Tahoka and Double Lakes formations. The eastern portion of the aquifer is at a high risk of exceeding maximum contaminant levels for arsenic, fluoride, and nitrate-N (Reedy and others, 2011).

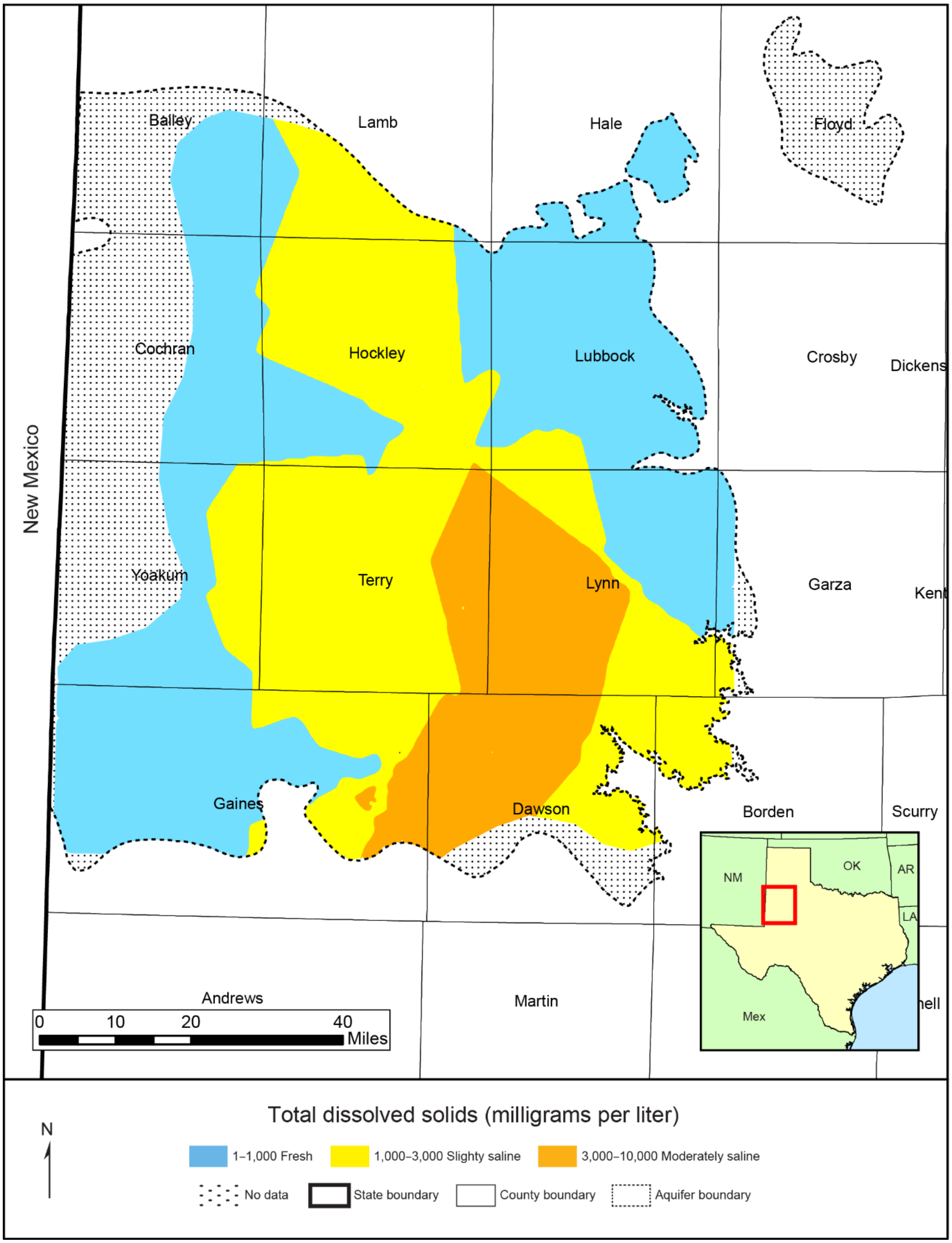


Figure 6-65. Total dissolved solids in the Edwards-Trinity (High Plains) Aquifer.

6.17 *Ellenburger-San Saba Aquifer*

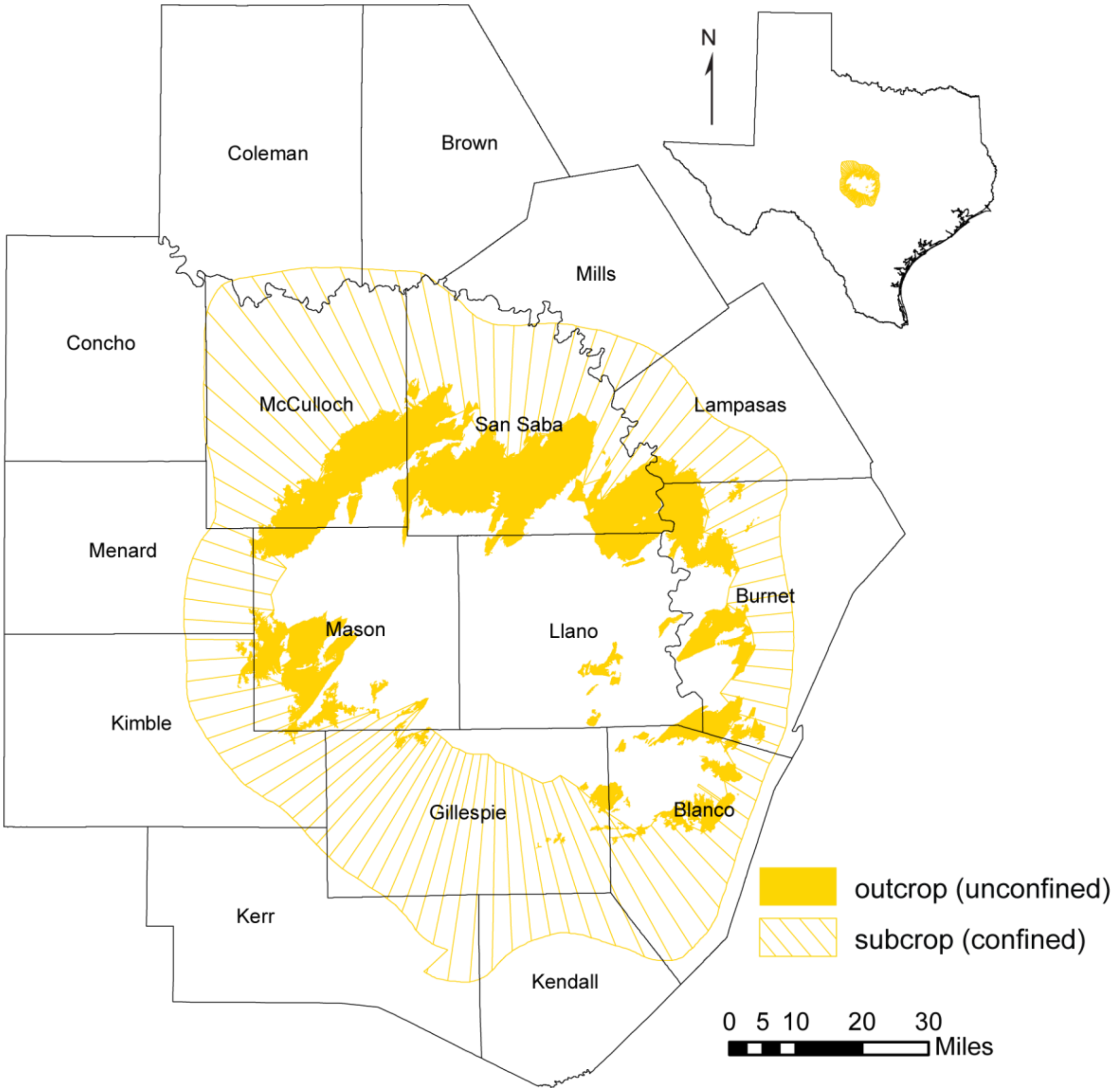


Figure 6-66. **Extent of the Ellenburger-San Saba Aquifer.**

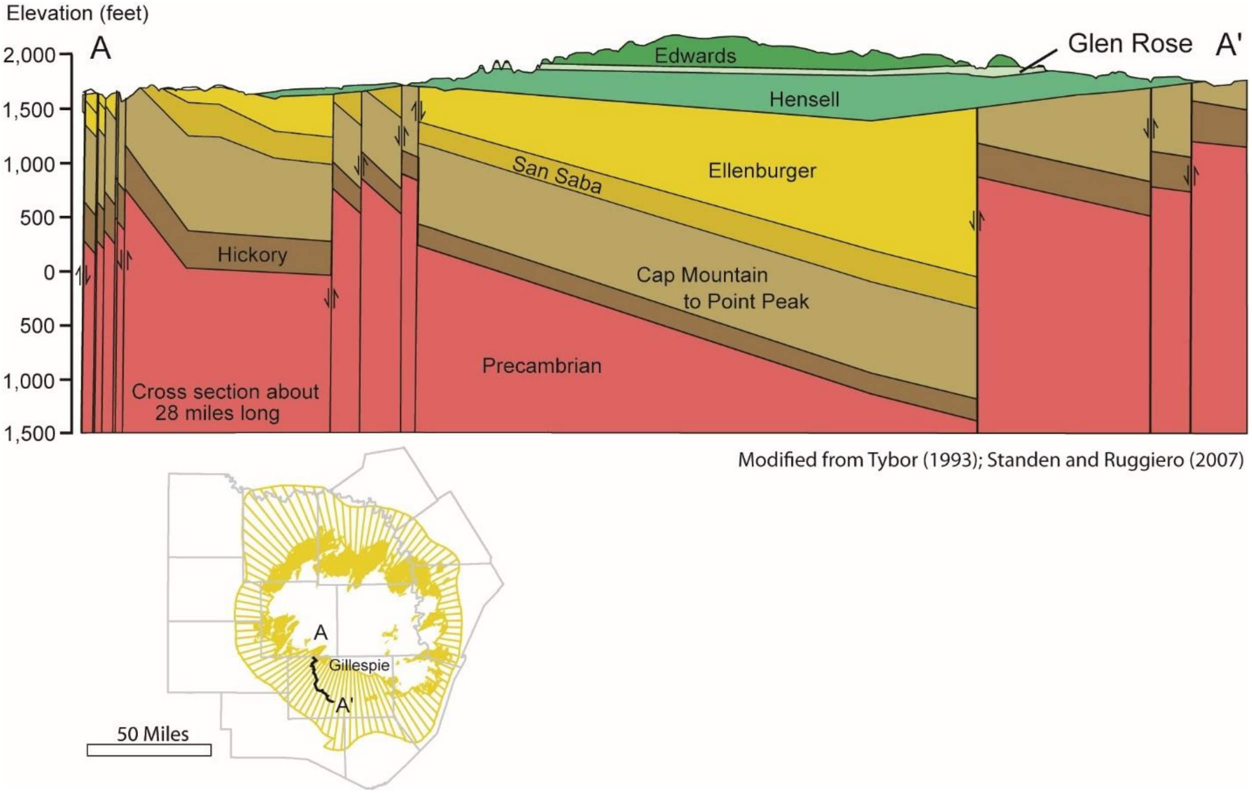
Aquifer characteristics

- Aquifer type: confined and unconfined
- Area of outcrop: 1,152 square miles
- Area in subsurface: 4,279 square miles
- Proportion of aquifer with groundwater conservation districts: 80 percent
- Number of counties containing the aquifer: 16

Geology and hydrogeology

The Ellenburger-San Saba Aquifer is a minor aquifer that is found in parts of 16 counties in the Llano Uplift area of Central Texas (Figure 6-66). The aquifer consists of a sequence of limestone and dolomite formations that crop out in a circular pattern around the uplift and dip radially into the subsurface to depths of approximately 3,000 feet (Figure 6-67). Regional block faulting has significantly compartmentalized the aquifer. The maximum thickness of the aquifer is about 2,700 feet.

Water occurs in fractures, cavities, and solution channels and is commonly under confined conditions. The aquifer is highly permeable in places, as indicated by wells that yield as much as 1,000 gallons per minute. Numerous springs issue from the aquifer, maintaining the baseflow of streams in the area.



Modified from Tybor (1993); Standen and Ruggiero (2007)

Figure 6-67. **Structural cross-section across the Ellenburger-San Saba Aquifer (modified from Tybor, 1993; Standen and Ruggiero, 2007).**

Flows to surface water and other aquifers

Precipitation and runoff contribute recharge to the Ellenburger-San Saba Aquifer in upland areas, with discharge occurring as stream baseflow at lower elevations. Faulting around the Llano Uplift and dissolution features in carbonate formations produce locally complex groundwater and surface-water interactions. Table 6-46 shows a summary of baseflow in the outcrop areas of the Ellenburger-San Saba Aquifer. Table 6-47 shows groundwater availability model estimates of total flow and average annual flow between the Ellenburger-San Saba Aquifer and other aquifers. Because of local differences in topography and structural off-sets along faults, flows may occur in both directions between aquifers.

Table 6-46. Summary of groundwater flow from the Ellenburger-San Saba Aquifer to surface water.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Blanco	36	2	0.5
Burnet	168	9.3	1.8
Gillespie	13	0.7	0.2
Kimble	7	0.4	0.2
Lampasas	17	0.9	0.2
Llano	62	2.8	0.9
Mason	182	7.3	2.8
McCulloch	172	3.1	0.9
Menard	1	0	0
San Saba	436	13.6	3
Total	**1,094**	**40**	**11**

Table 6-47. Model estimates of inter-aquifer flows between the Ellenburger-San Saba Aquifer and other major and minor aquifers.

Flow from	Flow to	Total flow (acre-feet per year)
Ellenburger-San Saba Aquifer	Hickory Aquifer	9,305
Ellenburger-San Saba Aquifer	Marble Falls Aquifer	2,368
Edwards-Trinity (Plateau) Aquifer	Ellenburger-San Saba Aquifer	929
Hickory Aquifer	Ellenburger-San Saba Aquifer	21,654
Marble Falls Aquifer	Ellenburger-San Saba Aquifer	3,647
Trinity Aquifer	Ellenburger-San Saba Aquifer	1,285

Water quantity

Total storage in the Ellenburger-San Saba Aquifer is estimated to be more than 87 million acre-feet. Recoverable storage is estimated to be between 25 and 75 percent of the total, about 21.7 million to 65.2 million acre-feet (Table 6-48).

Table 6-48. Total estimated recoverable storage in the Ellenburger-San Saba Aquifer, by county, in acre-feet.

County	Total storage	25 percent of storage	75 percent of storage
Blanco	8,300,000	2,075,000	6,225,000
Brown	420,000	105,000	315,000
Burnet	8,100,000	2,025,000	6,075,000
Coleman	1,400,000	350,000	1,050,000
Concho	62,000	15,500	46,500
Gillespie	6,500,000	1,625,000	4,875,000
Kendall	3,500,000	875,000	2,625,000
Kerr	2,100,000	525,000	1,575,000
Kimble	6,000,000	1,500,000	4,500,000
Lampasas	8,500,000	2,125,000	6,375,000
Llano	350,000	87,500	262,500

Table 6-48 (continued). Total estimated recoverable storage in the Ellenburger-San Saba Aquifer, by county, in acre-feet.

County	Total storage	25 percent of storage	75 percent of storage
Mason	1,900,000	475,000	1,425,000
McCulloch	16,000,000	4,000,000	12,000,000
Menard	1,600,000	400,000	1,200,000
Mills	2,300,000	575,000	1,725,000
San Saba	20,000,000	5,000,000	15,000,000
Total	**87,032,000**	**21,758,000**	**65,274,000**

Water quality

Groundwater in the Ellenburger-San Saba Aquifer is generally very good and usually has less than 1,000 milligrams per liter of total dissolved solids (Figure 6-68). Total dissolved solids increase down-dip and radially outward from the Llano Uplift, centered in Llano County. Elevated concentrations of radionuclides also occur in the aquifer, mostly in the northern part of the aquifer (Reedy and others, 2011).

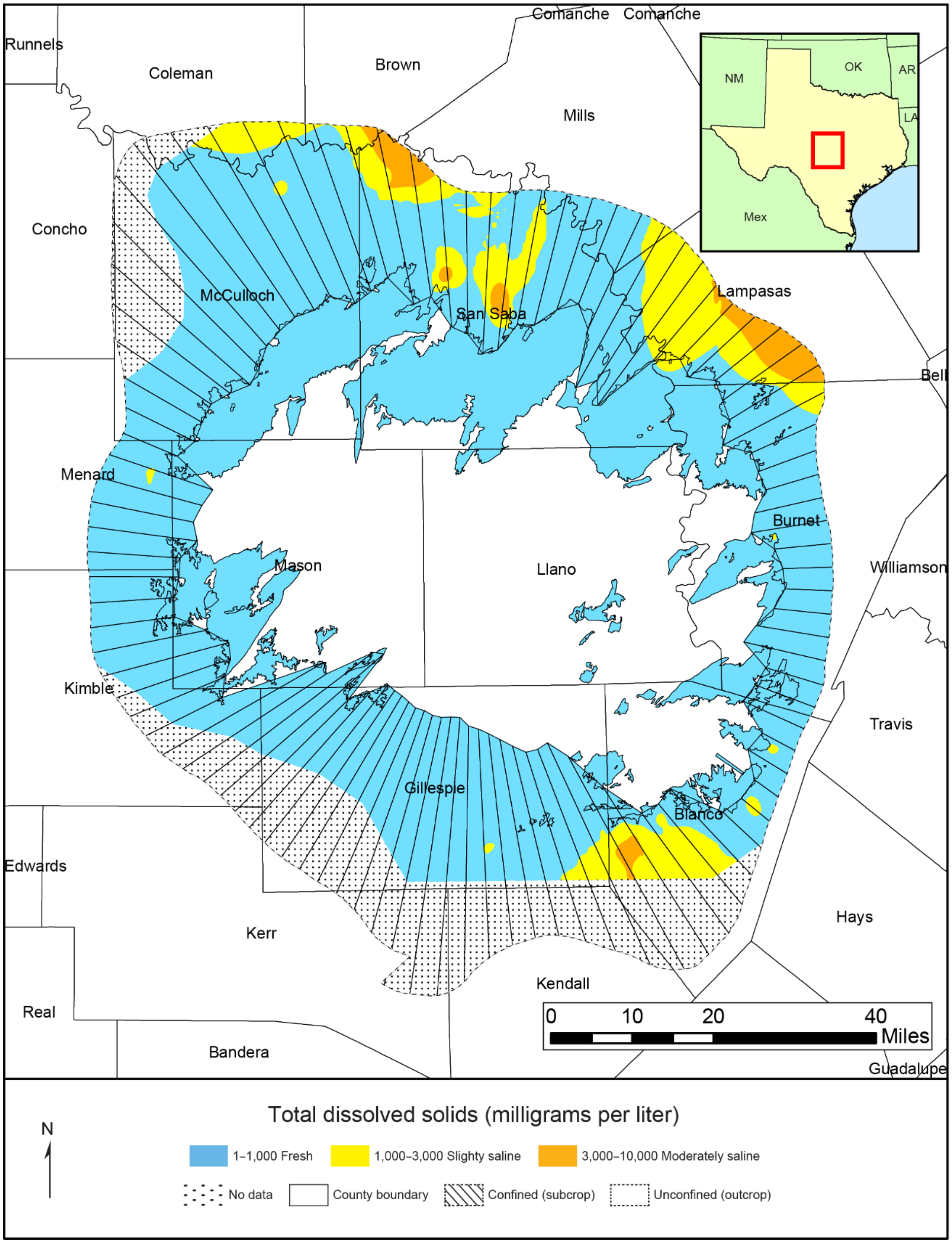


Figure 6-68. **Total dissolved solids in the Ellenburger-San Saba Aquifer.**

6.18 Hickory Aquifer

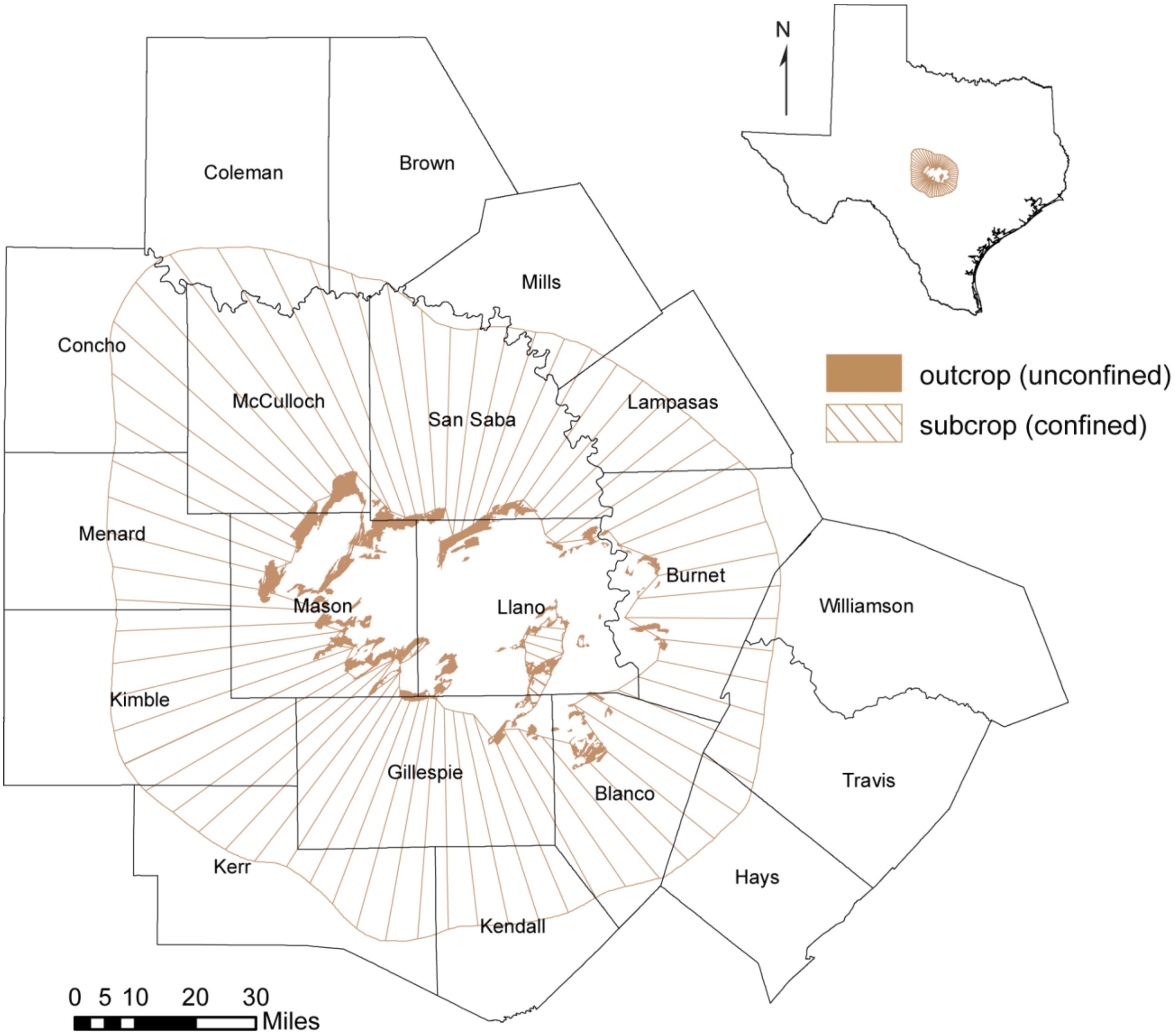


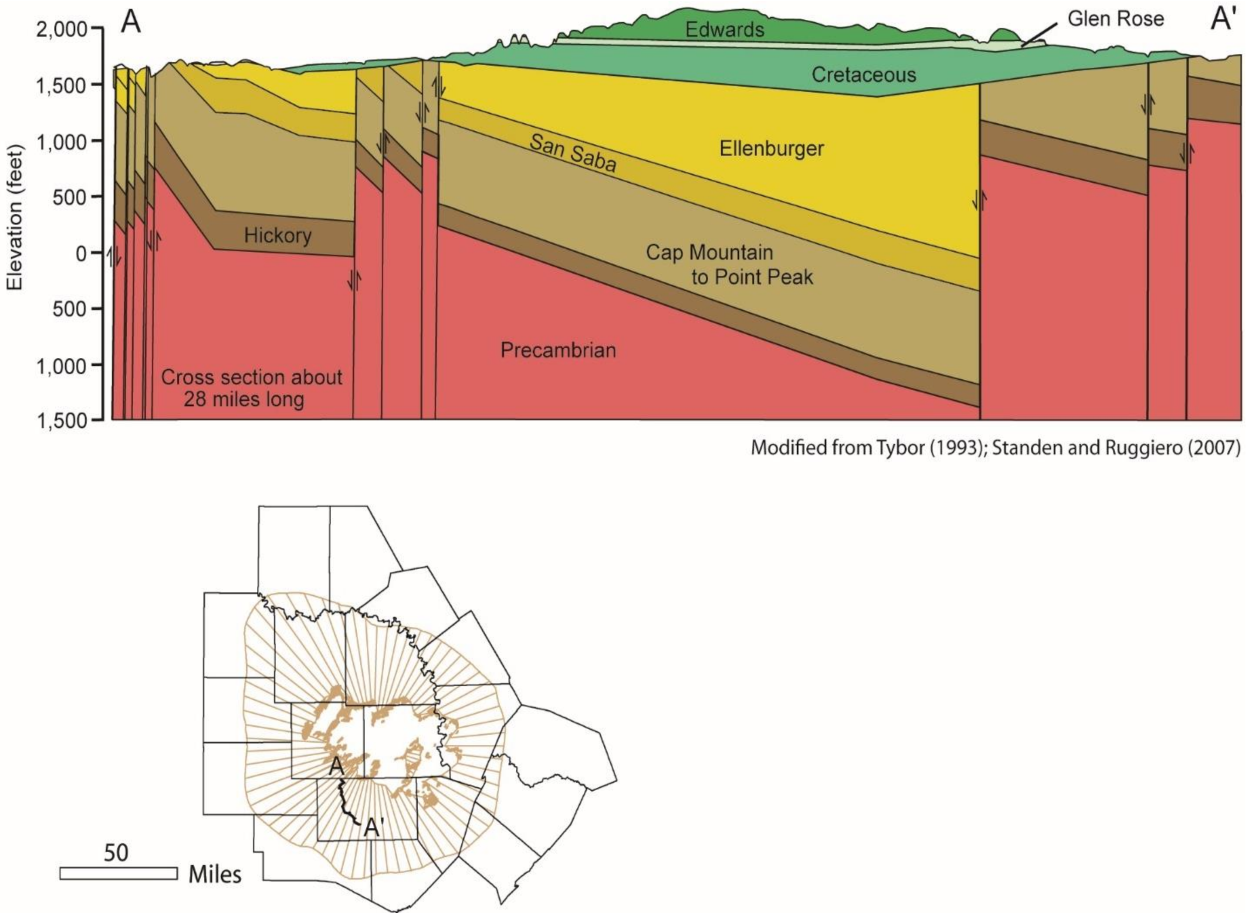
Figure 6-69. Extent of the Hickory Aquifer.

Aquifer characteristics

- Aquifer type: confined and unconfined
- Area of outcrop: 272 square miles
- Area in subsurface: 8,317 square miles
- Proportion of aquifer with groundwater conservation districts: 83 percent
- Number of counties containing the aquifer: 19

Geology and hydrogeology

The Hickory Aquifer is a minor aquifer in the central part of the state that consists of the water-bearing parts of the Hickory Sandstone Member (Figure 6-69). The Hickory Member is a mixture of terrestrial and marine sandstones, siltstones, and mudstones. It is divided into three units with quartz sand in the lower unit, silty or argillaceous sand in the middle unit, and hematite-cemented sand in the upper unit (Shi and others, 2016b). In general, the Hickory Member thickens from north to south, with zero thickness at the Precambrian granite knobs of the Llano Uplift to about 1,000 feet in Kerr County to the south (Figure 6-70). The top and base of the Hickory Member are strong geophysical log correlation surfaces (Standen and Ruggiero, 2007) with relatively high gamma readings. The freshwater saturated thickness of the Hickory Aquifer averages about 350 feet.



Modified from Tybor (1993); Standen and Ruggiero (2007)

Figure 6-70. **Structural cross-section across the Hickory Aquifer (modified from Tybor, 1993; Standen and Guggiero, 2007).**

Flows to surface water and other aquifers

Inflow to the Hickory Aquifer occurs as cross-formational flow from younger units and recharge by precipitation in the outcrop area. Outflow includes groundwater pumping, leakage to surface-water bodies, and cross-formational flow to the Ellenburger-San Saba Aquifer (Shi and others, 2016a). Table 6-49 summarizes baseflow in the outcrop areas of the Hickory Aquifer by county. Table 6-50 shows groundwater availability model estimates of total flow and average annual flow between the Hickory Aquifer and other aquifers.

Table 6-49. Summary of groundwater flow from the Hickory Aquifer to surface water, by county.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Blanco	18	1	0.2
Burnet	13	0.7	0.1
Gillespie	12	0.6	0.2
Llano	62	2.6	0.9
Mason	117	4.6	1.7
McCulloch	22	0.5	0.2
San Saba	25	0.9	0.3
Total	**269**	**11**	**4**

Table 6-50. Model estimates of inter-aquifer flows between the Hickory Aquifer and other major and minor aquifers.

Flow from	Flow to	Total flow (acre-feet per year)
Hickory Aquifer	Ellenburger-San Saba Aquifer	21,654
Hickory Aquifer	Trinity Aquifer	64
Edwards-Trinity (Plateau) Aquifer	Hickory Aquifer	43
Ellenburger-San Saba Aquifer	Hickory Aquifer	9,305

Water quantity

Total storage in the Hickory Aquifer is estimated to be more than 66 million acre-feet. Recoverable storage is estimated to be between 25 and 75 percent of the total, about 16.5 million to 49.6 million acre-feet (Table 6-51).

Table 6-51. Total estimated recoverable storage in the Hickory Aquifer, by county, in acre-feet.

County	Total storage	25 percent of storage	75 percent of storage
Blanco	4,700,000	1,175,000	3,525,000
Brown	220,000	55,000	165,000
Burnet	6,600,000	1,650,000	4,950,000
Coleman	1,500,000	375,000	1,125,000
Concho	2,800,000	700,000	2,100,000
Gillespie	7,200,000	1,800,000	5,400,000
Kimble	5,900,000	1,475,000	4,425,000
Lampasas	2,800,000	700,000	2,100,000
Llano	1,000,000	250,000	750,000
Mason	5,400,000	1,350,000	4,050,000
McCulloch	8,500,00	2,125,000	3,375,000
Menard	4,500,000	1,125,000	3,375,000
Mills	630,000	157,500	472,500
San Saba	7,500,000	1,875,000	5,625,000
Williamson	17,000	4,250	12,750
Total	**66,182,000**	**16,545,500**	**49,636,500**

Water quality

Groundwater is mostly fresh with less than 1,000 milligrams per liter of total dissolved solids. Excess iron in the upper portion of the aquifer may result in poor-tasting water and may exceed drinking water standards. Additionally, naturally occurring radioactivity may exceed the state's primary drinking standards (Reedy and others, 2011) and require additional treatment or blending. Radionuclides are derived from the Precambrian granite rocks in the Llano Uplift (Reedy and others, 2011).

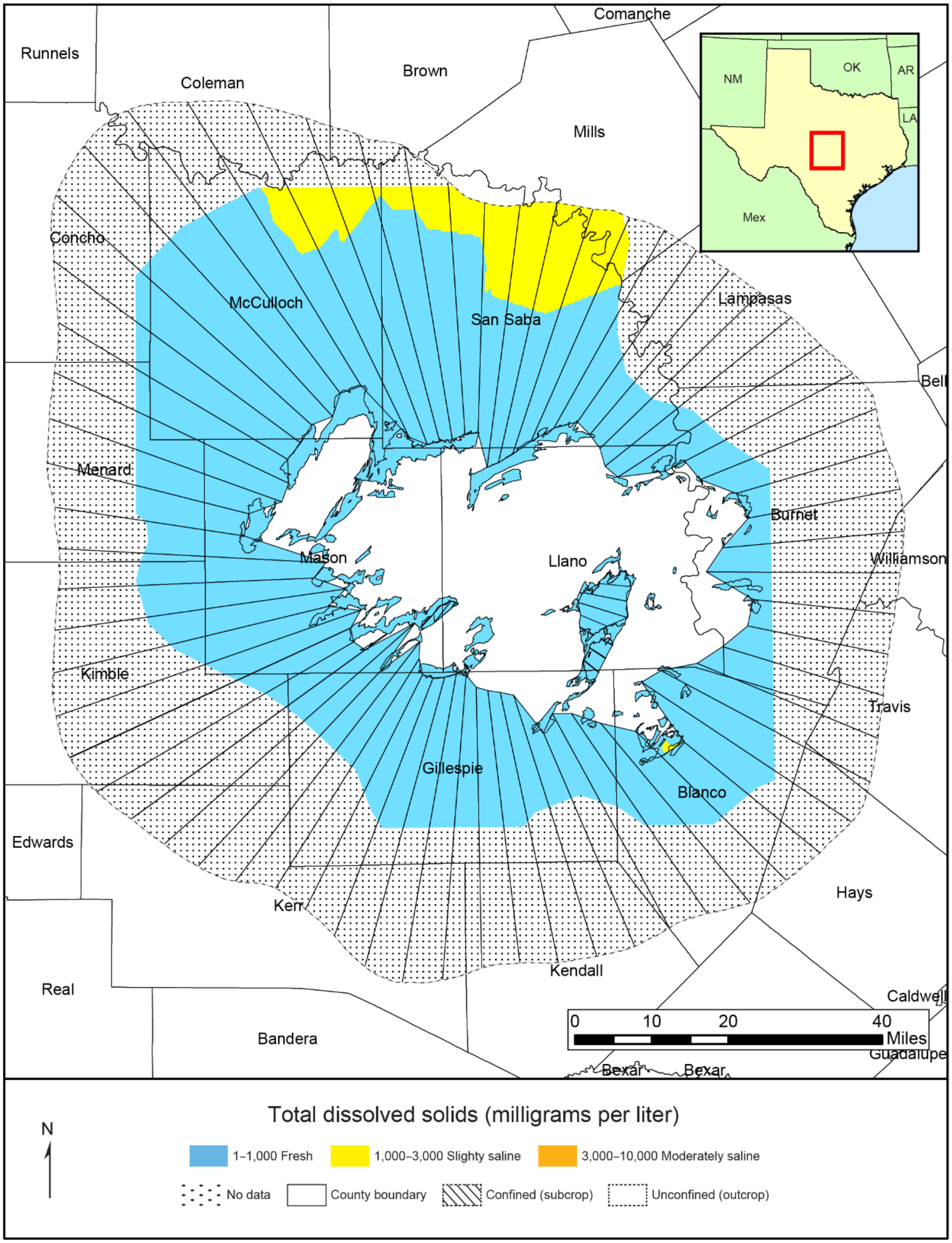


Figure 6-71. Total dissolved solids in the Hickory Aquifer.

6.19 Igneous Aquifer

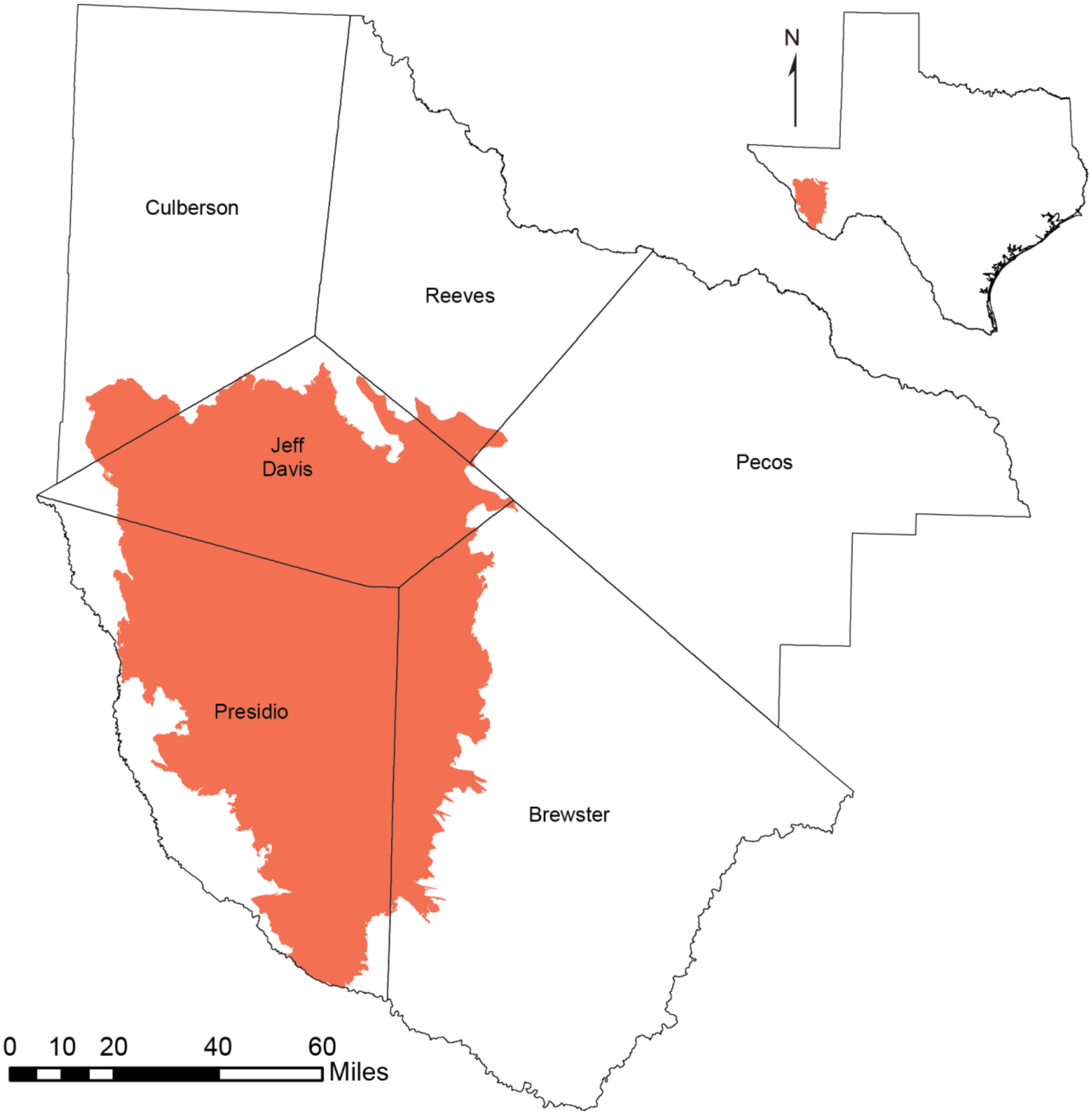


Figure 6-72. Extent of the Igneous Aquifer.

Aquifer characteristics

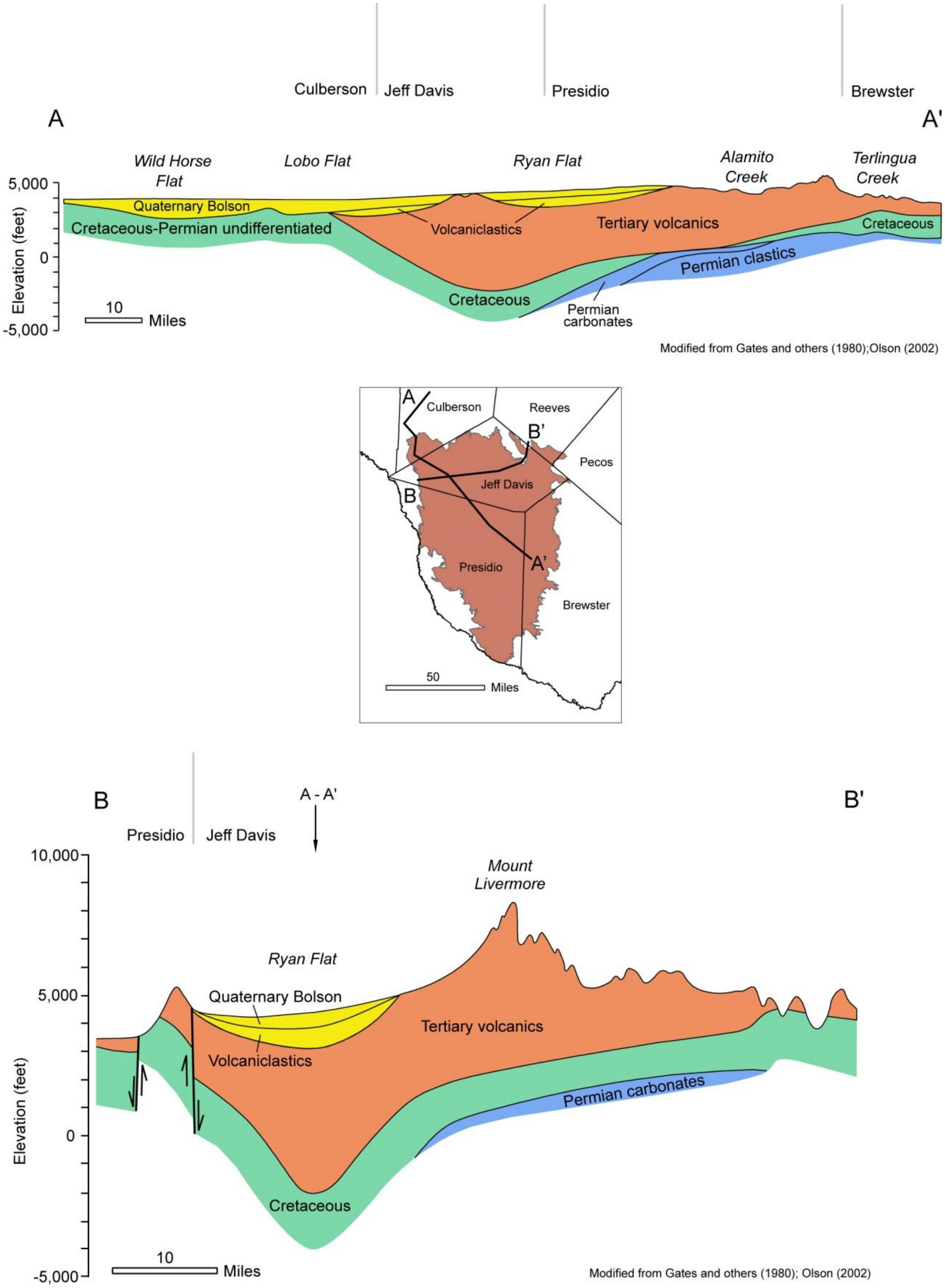
- Aquifer type: unconfined
- Area of aquifer: 6,075 square miles
- Proportion of aquifer with groundwater conservation districts: 100 percent
- Number of counties containing the aquifer: 6

Geology and hydrogeology

The Igneous Aquifer is a minor aquifer located in far west Texas (Figure 6-72). The aquifer consists of volcanic rocks made up of a complex series of welded pyroclastic rock, lava, and volcaniclastic sediments as much as 6,000 feet thick (Figure 6-73). Freshwater saturated thickness averages about 1,800 feet. The best water-bearing zones are found in igneous rocks with primary porosity and permeability, such as vesicular basalts, interflow zones in lava successions, sandstone, conglomerate, and breccia. Faulting and fracturing enhance aquifer productivity in less permeable rock units.

Flows to surface water and other aquifers

Baseflow analysis indicates that the Igneous Aquifer discharges limited amounts of groundwater to surface water in its outcrop area. Table 6-52 summarizes baseflow from the Igneous Aquifer by county. Two different groundwater availability models cover the area of the Igneous Aquifer. Both employ a no-flow boundary in the area of contact between the Igneous and West Texas Bolsons aquifers and, consequently, no modeled inter-aquifer flow between the Igneous Aquifer and other major and minor aquifers is available. An analytical approach suggests an average annual flow of approximately 3,500 acre-feet per year from the Igneous Aquifer to the Presidio-Redford Bolsons Aquifer.



Modified from Gates and others (1980);Olson (2002)

Modified from Gates and others (1980); Olson (2002)

Figure 6-73. **Structural cross-sections across the Igneous Aquifer (modified from Gates and others, 1980; Olson, 2002; Beach and others, 2004).**

Table 6-52. Summary of groundwater flow from the Igneous Aquifer to surface water, by county.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Brewster	897	3.3	0.7
Culberson	91	0.5	0.3
Jeff Davis	1,692	8.4	3.2
Pecos	9	0	0
Presidio	2,642	13	5.9
Reeves	74	0.1	0.2
Total	**5,405**	**25**	**10**

Water quantity

Total storage in the Igneous Aquifer is estimated to be more than 64 million acre-feet. Recoverable storage is estimated to be between 25 and 75 percent of the total, or about 16 million to 48 million acre-feet (Table 6-53).

Table 6-53. Total estimated recoverable storage in the Igneous Aquifer, by county, in acre-feet.

County	Total storage	25 percent of storage	75 percent of storage
Brewster	5,300,000	1,325,000	3,975,000
Culberson	760,000	190,000	570,000
Jeff Davis	24,000,000	6,000,000	18,000,000
Pecos	350	88	263
Presidio	34,000,000	8,500,000	25,500,000
Reeves	54,000	13,500	40,500
Total	**64,114,350**	**16,028,588**	**48,085,763**

Water quality

Water in the Igneous Aquifer is fresh and contains less than 1,000 milligrams per liter of total dissolved solids (Figure 6-74). Groundwater from some wells contains elevated levels of silica and fluoride, as a result of weathering of the igneous rock that makes up the aquifer. Groundwater in a few wells exceeds maximum contaminant levels for arsenic, fluoride, and gross alpha radiation (Reedy and others, 2011).

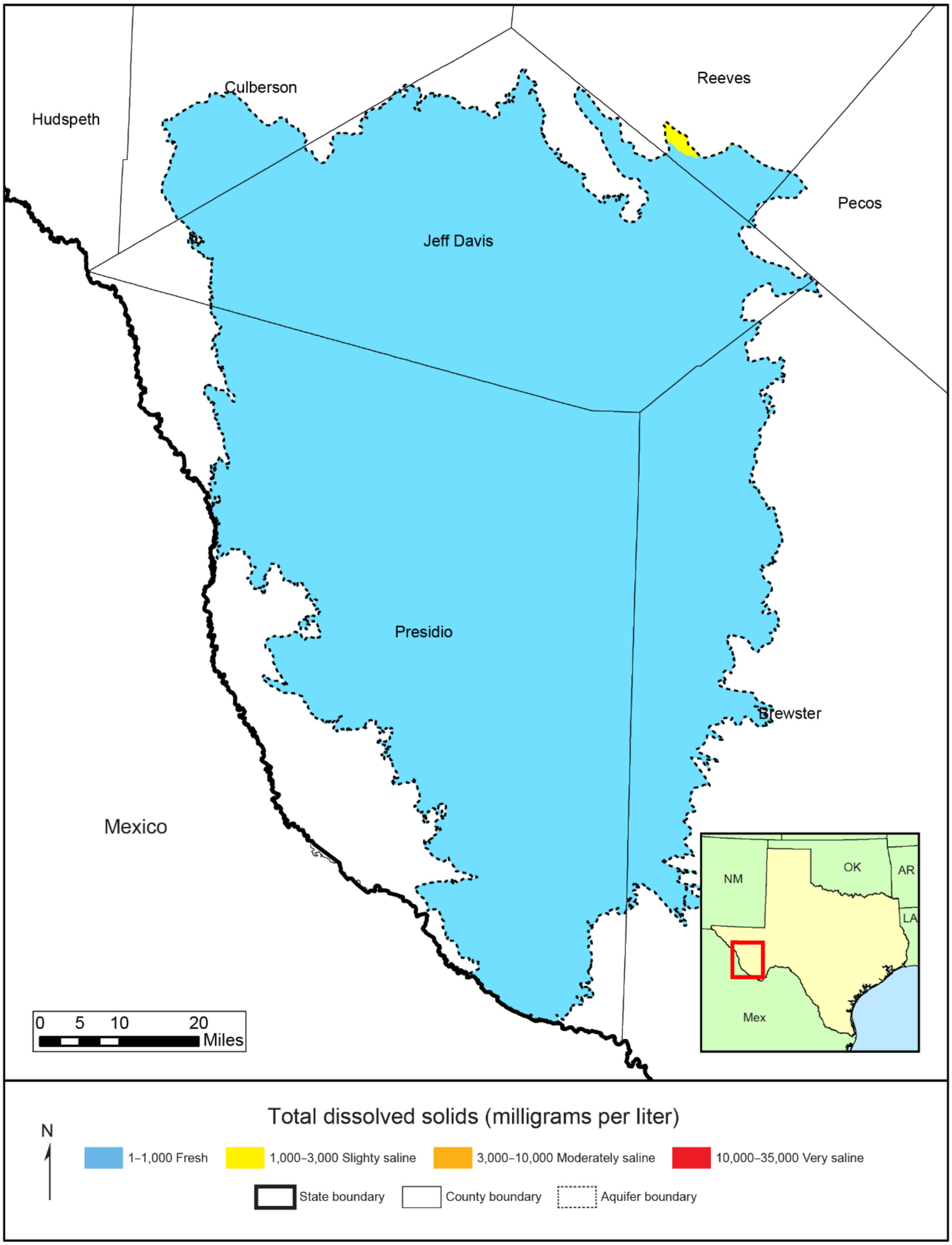


Figure 6-74. Total dissolved solids in the Igneous Aquifer.

6.20 Lipan Aquifer

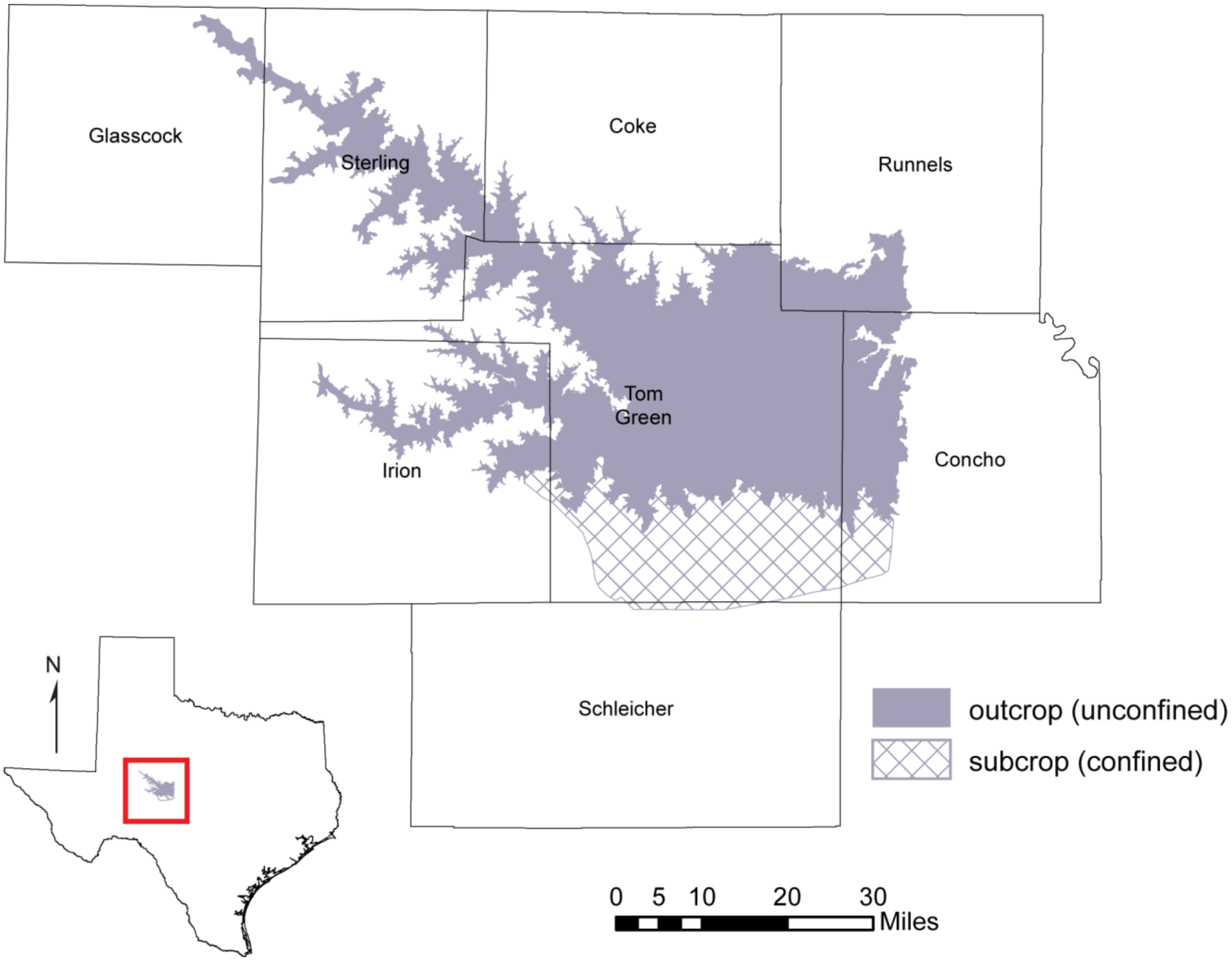


Figure 6-75. Extent of the Lipan Aquifer.

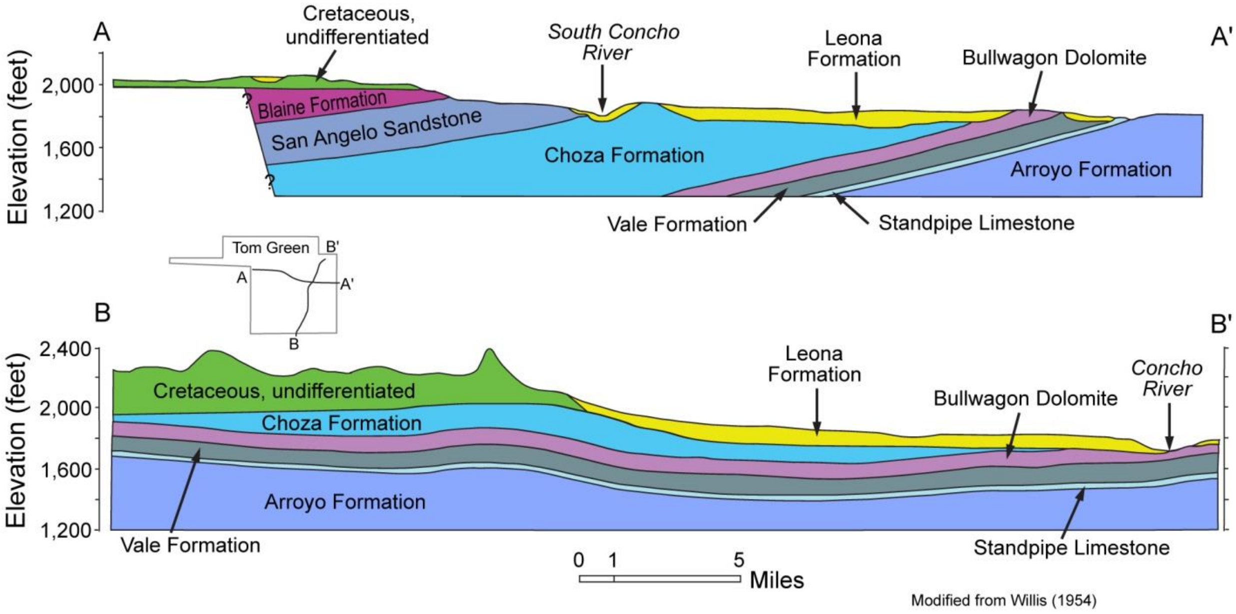
Aquifer characteristics

- Aquifer type: confined and unconfined
- Area of outcrop: 1,571 square miles
- Area in subsurface: 424 square miles
- Proportion of aquifer with groundwater conservation districts: 85 percent
- Number of counties containing the aquifer: 8

Geology and hydrogeology

The Lipan Aquifer is a minor aquifer in west central Texas (Figure 6-75). The aquifer includes water-bearing alluvium and the up-dip portions of older strata underlying the alluvium. The alluvium includes as much as 125 feet of saturated sediments of the Quaternary Leona Formation. These deposits consist mostly of gravels and conglomerates cemented with sandy lime and layers of clay. The formation generally fines upward with conglomerates existing mainly in locations of thicker alluvium. The underlying strata include the San Angelo Sandstone of the Pease River Group and the Choza Formation, Bullwagon Dolomite, Vale Formation, Standpipe Limestone, and Arroyo Formation of the Permian-age Clear Fork Group (Figure 6-76). These units are predominantly limestones and shales.

The alluvial deposits and the upper parts of the older rocks are hydraulically connected. Groundwater flow in the Lipan Aquifer does not appear to be structurally controlled. Higher-production wells appear to correspond to alluvial deposits overlying the Choza, Bullwagon, and Vale formations. In these areas, thick alluvial deposits with conglomerates lie near the contact with the Permian formations.



Modified from Willis (1954)

Figure 6-76. Structural cross-sections across the Lipan Aquifer in Tom Green County, Texas. A-A′, west to east; B-B′, south to north (modified from Willis, 1954).

Flows to surface water and other aquifers

The Concho River is a major discharge and recharge feature of the Lipan Aquifer. However, net discharge from the Lipan Aquifer in the form of river baseflow is fairly small, and during a recent drought the Concho River flow ceased between San Angelo and Paint Rock (Beach and others, 2004). Table 6-54 shows a summary of baseflow in the outcrop areas of the Lipan Aquifer.

Table 6-55 shows groundwater availability model estimates of total flow and average annual flow between the Lipan Aquifer and other aquifers. Groundwater flows from the Edwards-Trinity (Plateau) Aquifer to the Lipan Aquifer in Coke, Irion, Runnels, and Schleicher counties, while in Concho and Tom Green counties the flow direction is reversed.

Table 6-54. Summary of groundwater flow from the Lipan Aquifer to surface water, by county.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Coke	37	0.2	0.1
Concho	153	0.9	0.3
Glasscock	19	0	0
Irion	151	2.2	1.1
Runnels	88	0.3	0
Sterling	203	0.7	0.4
Tom Green	920	7.1	2.1
Total	**1,571**	**11**	**4**

Table 6-55. Model estimates of inter-aquifer flows between the Lipan Aquifer and other major and minor aquifers.

Flow from	Flow to	Total flow (acre-feet per year)
Lipan Aquifer	Edwards-Trinity (Plateau) Aquifer & Other Formations	7,506
Edwards-Trinity (Plateau) Aquifer & Other Formations	Lipan Aquifer	7,507

Water quantity

Total storage in the Lipan Aquifer is estimated to be about 4 million acre-feet. Recoverable storage is estimated to be between 25 and 75 percent of the total, about 1 million to 3.1 million acre-feet (Table 6-56).

Table 6-56. Total estimated recoverable storage in the Lipan Aquifer, by county, in acre-feet.

County	Total storage	25 percent of storage	75 percent of storage
Coke	13,000	3,250	9,750
Concho	720,000	180,000	540,000
Glasscock	6,000	1,500	4,500
Irion	100,000	25,000	75,000
Runnels	400,000	100,000	300,000
Schleicher	7,500	1,875	5,625
Sterling	41,000	10,250	30,750
Tom Green	2,900,000	725,000	2,175,000
Total	**4,200,000**	**1,046,875**	**3,140,625**

Water quality

Water quality in the alluvium is very hard and ranges from fresh to slightly saline, containing between 350 and 3,000 milligrams per liter of total dissolved solids (Figure 6-77). Water in the underlying parts of the Choza Formation and Bullwagon Dolomite tends to be moderately saline with total dissolved solids in excess of 3,000 milligrams per liter. The central region of the aquifer has a high probability of exceeding the maximum contaminant level for total dissolved solids. The eastern portion of the aquifer has the highest probability of exceeding the maximum contaminant level for nitrate (Reedy and others, 2011).

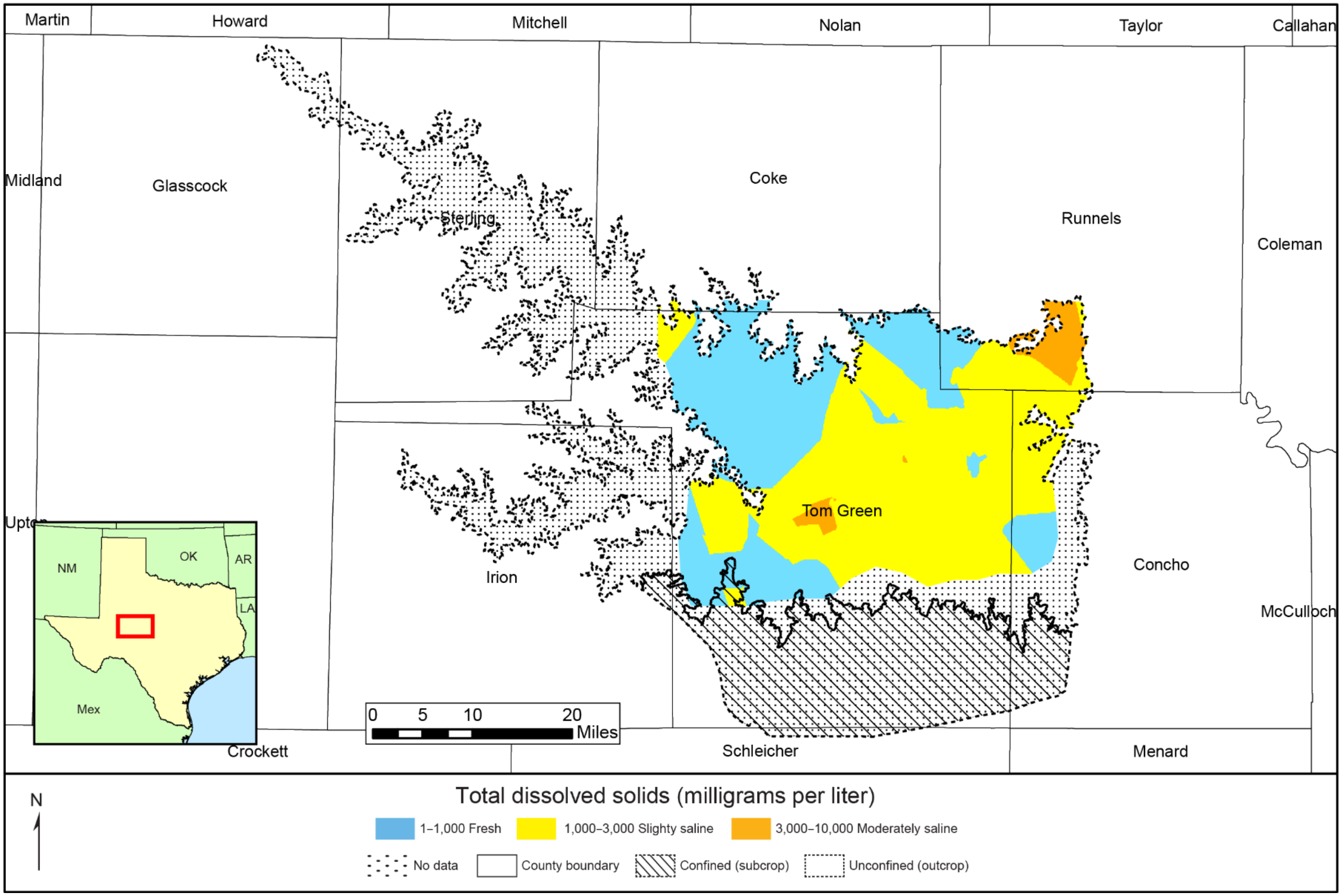


Figure 6-77. **Total dissolved solids in the Lipan Aquifer.**

6.21 Marathon Aquifer

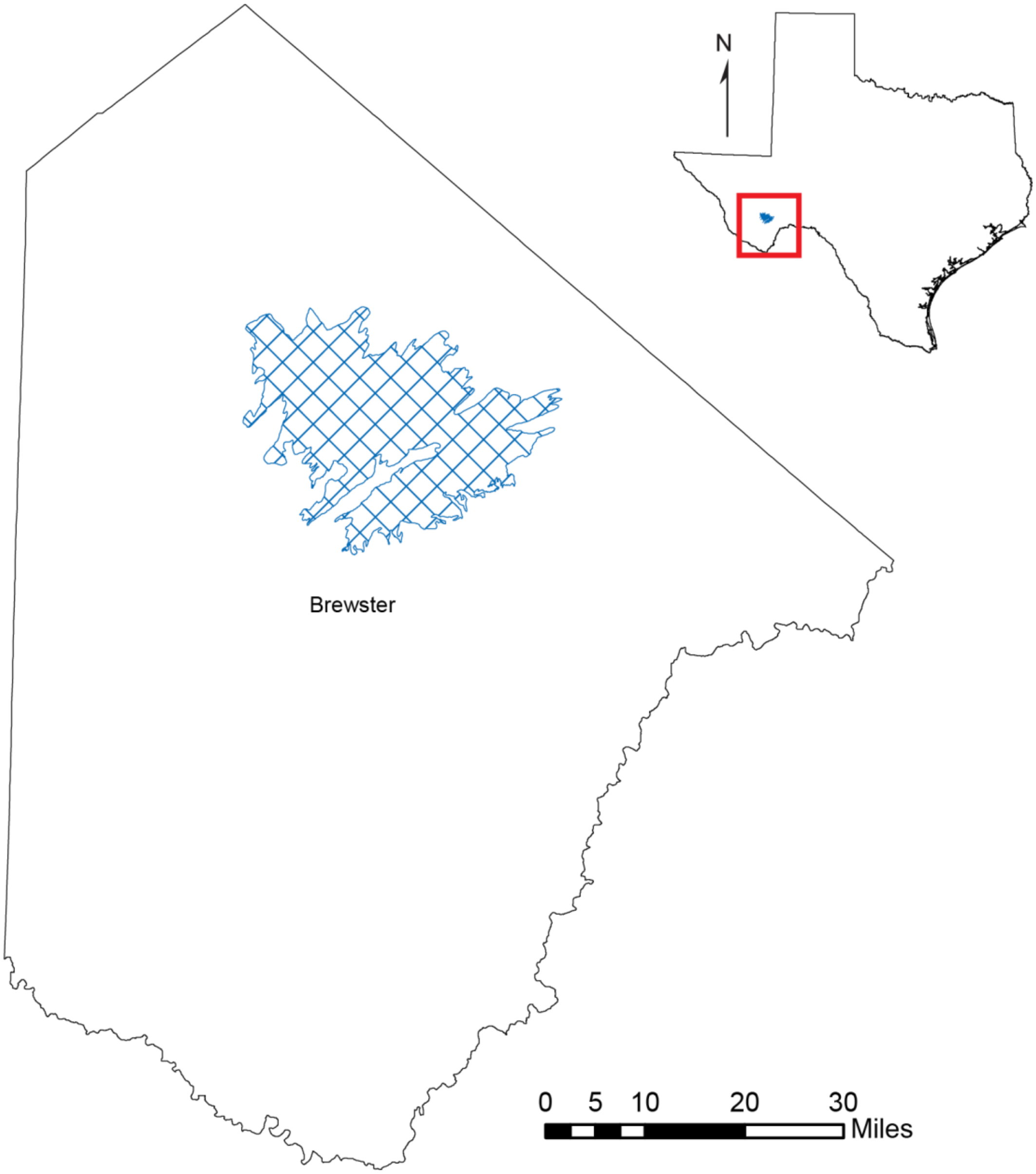


Figure 6-78. Extent of the Marathon Aquifer.

Aquifer characteristics

- Aquifer type: unconfined with locally confined areas
- Area of outcrop: 391 square miles
- Proportion of aquifer with groundwater conservation districts: 100 percent
- Number of counties containing the aquifer: 1

Geology and hydrogeology

The Marathon Aquifer, a minor aquifer, occurs entirely within north central Brewster County (Figure 6-78). The aquifer consists of tightly folded and faulted rocks of the Gaptank Formation, the Dimple Limestone, the Tesnus Formation, the Caballos Novaculite, the Maravillas Chert, the Fort Peña Formation, and the Marathon Limestone (Figure 6-79). Although the maximum thickness of the aquifer is about 900 feet, well depths are commonly less than 250 feet. Water in the aquifer is generally under unconfined conditions and is contained in fractures, joints, and cavities in the limestone. Groundwater is locally confined in areas where the aquifer is buried beneath impermeable formations, such as in the town of Marathon, and may rise a few feet above the depth at which it is first encountered. The Marathon Limestone is the most productive part of the aquifer. Many of the shallow wells in the region actually produce water from alluvial deposits that cover parts of the rock formations. Well yields range from less than 10 gallons per minute to more than 300 gallons per minute; the highest yields occur within a fault zone in the town of Marathon (Smith, 2001).

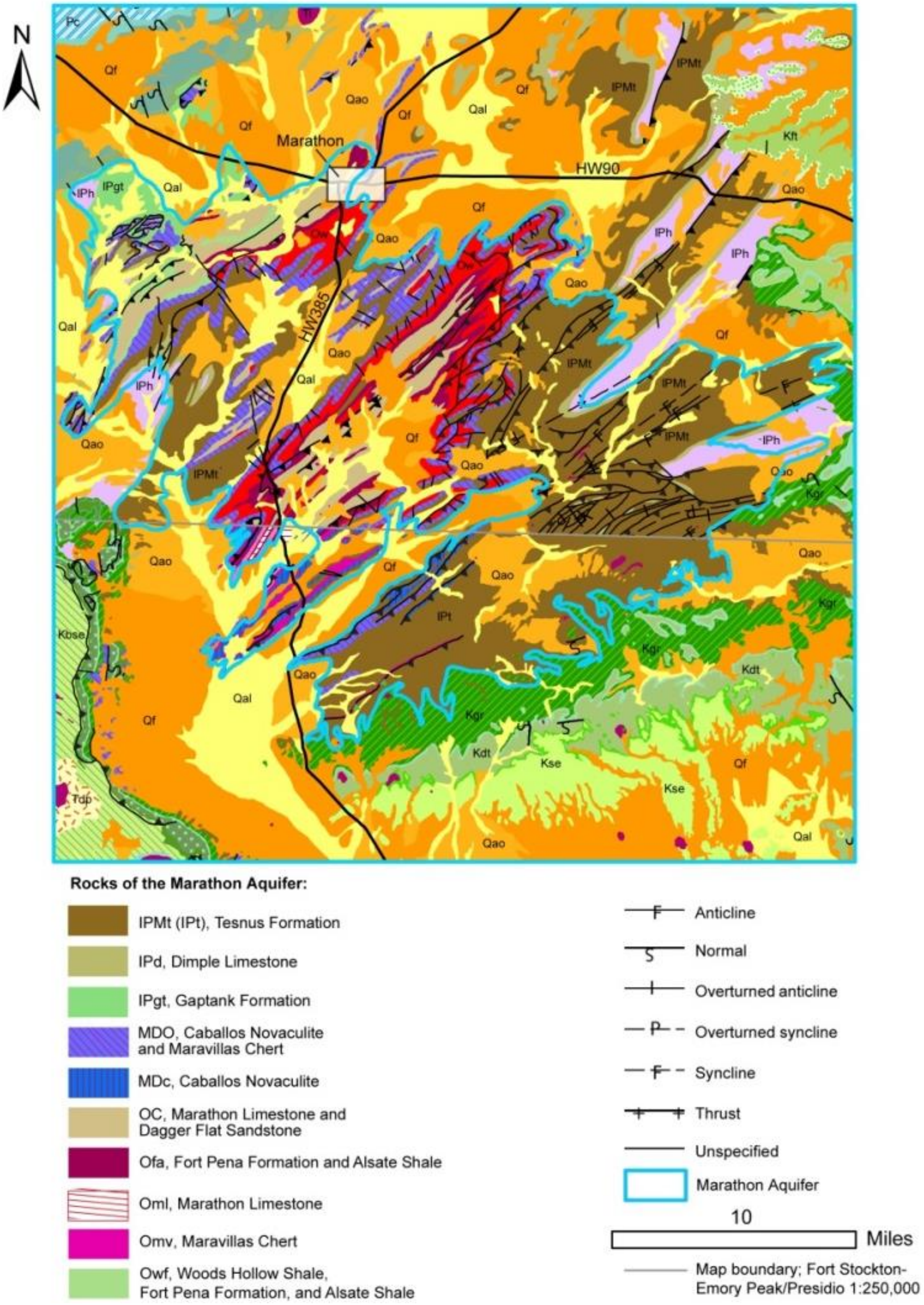


Figure 6-79. **Geologic map across the Marathon Aquifer (USGS and TWDB, 2006).**

Flows to surface water and other aquifers

Table 6-57 summarizes baseflow from the Marathon Aquifer. The Marathon Aquifer discharges at Peña Colorada Springs near Marathon, and at smaller springs along creeks in the area. The Marathon Aquifer is not in contact with any other major or minor aquifers; consequently, no inter-aquifer flows are expected.

Table 6-57. Summary of groundwater flow from the Marathon Aquifer to surface water.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Brewster	391	2.8	1

Water quantity

Total storage in the Marathon Aquifer is estimated to be 1.5 million acre-feet. Recoverable storage is estimated to be between 25 and 75 percent of the total, about 375,000 to 1.1 million acre-feet (Table 6-58).

Table 6-58. Total estimated recoverable storage in the Marathon Aquifer.

County	Total storage	25 percent of storage	75 percent of storage
Brewster	1,500,000	375,000	1,125,000

Water quality

Total dissolved solids range from 500 to 1,000 milligrams per liter, and the water, although very hard, is generally suitable for most uses (Figure 6-80).

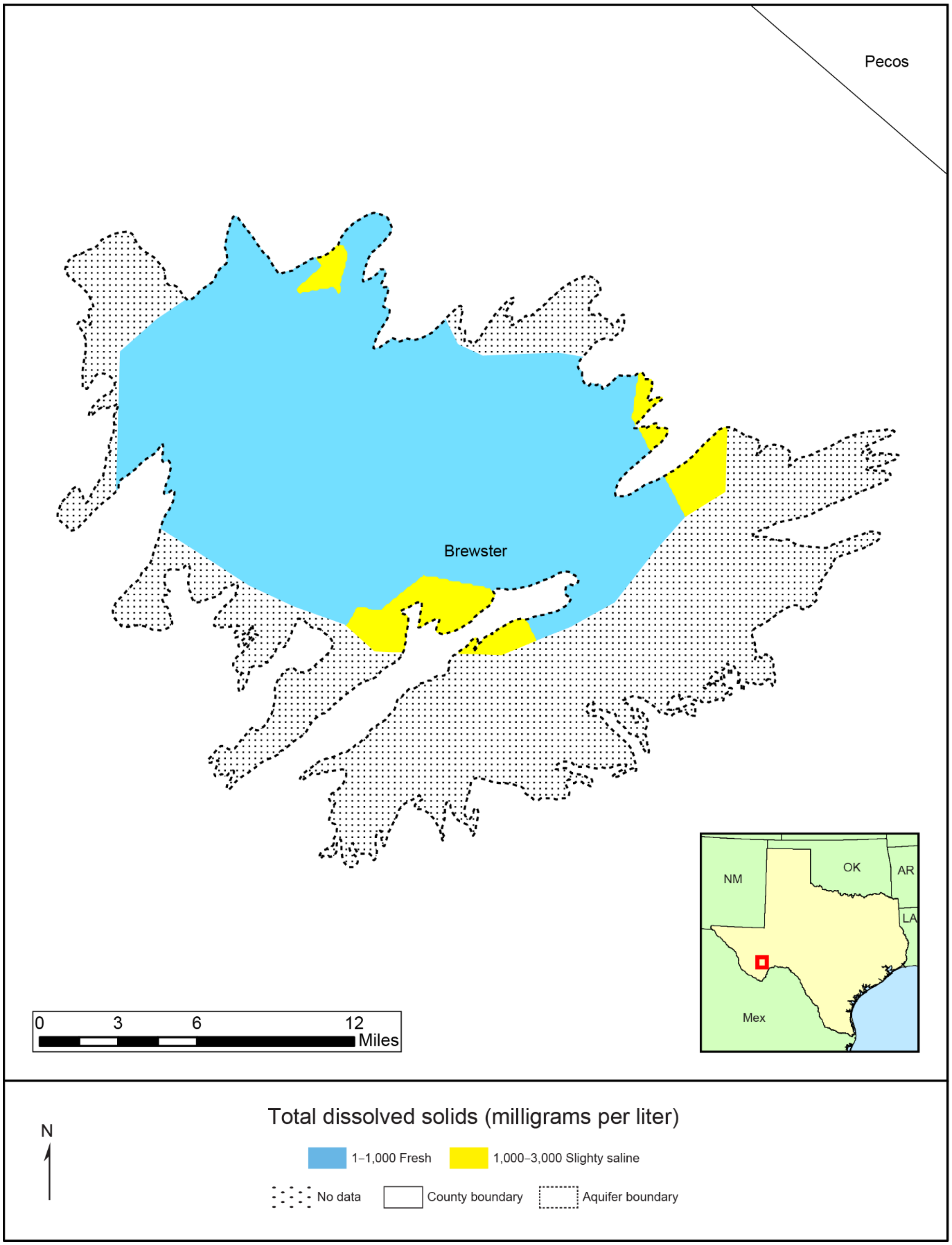


Figure 6-80. Total dissolved solids in the Marathon Aquifer.

6.22 Marble Falls Aquifer

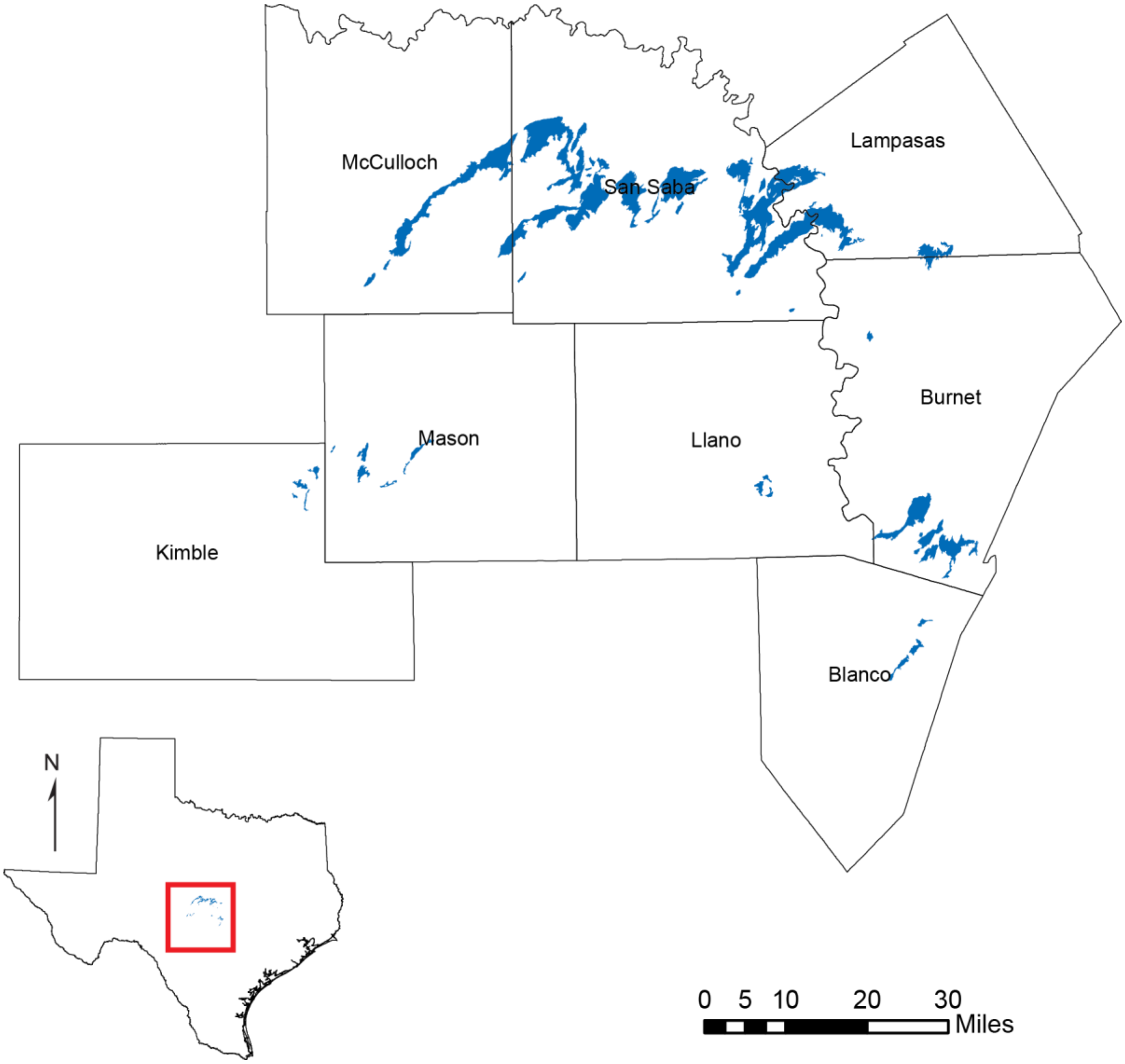


Figure 6-81. Extent of the Marble Falls Aquifer.

Aquifer characteristics

- Aquifer type: unconfined
- Area of outcrop: 215 square miles
- Proportion of aquifer with groundwater conservation districts: 78 percent
- Number of counties containing the aquifer: 8

Geology and hydrogeology

The Marble Falls Aquifer is a minor aquifer that occurs in several separated outcrops along the northern and eastern edges of the Llano Uplift in Central Texas (Figure 6-81). The subsurface extent of the aquifer is largely unknown. Water occurs in the Marble Falls Limestone in voids and fractures, and the formation is very permeable in some areas. Wells may produce up to 2,000 gallons per minute and the formation measures up to 600 feet thick with an average estimated thickness of 160 feet. Specific yield estimates range from 1.5 percent to as much as 3 percent.

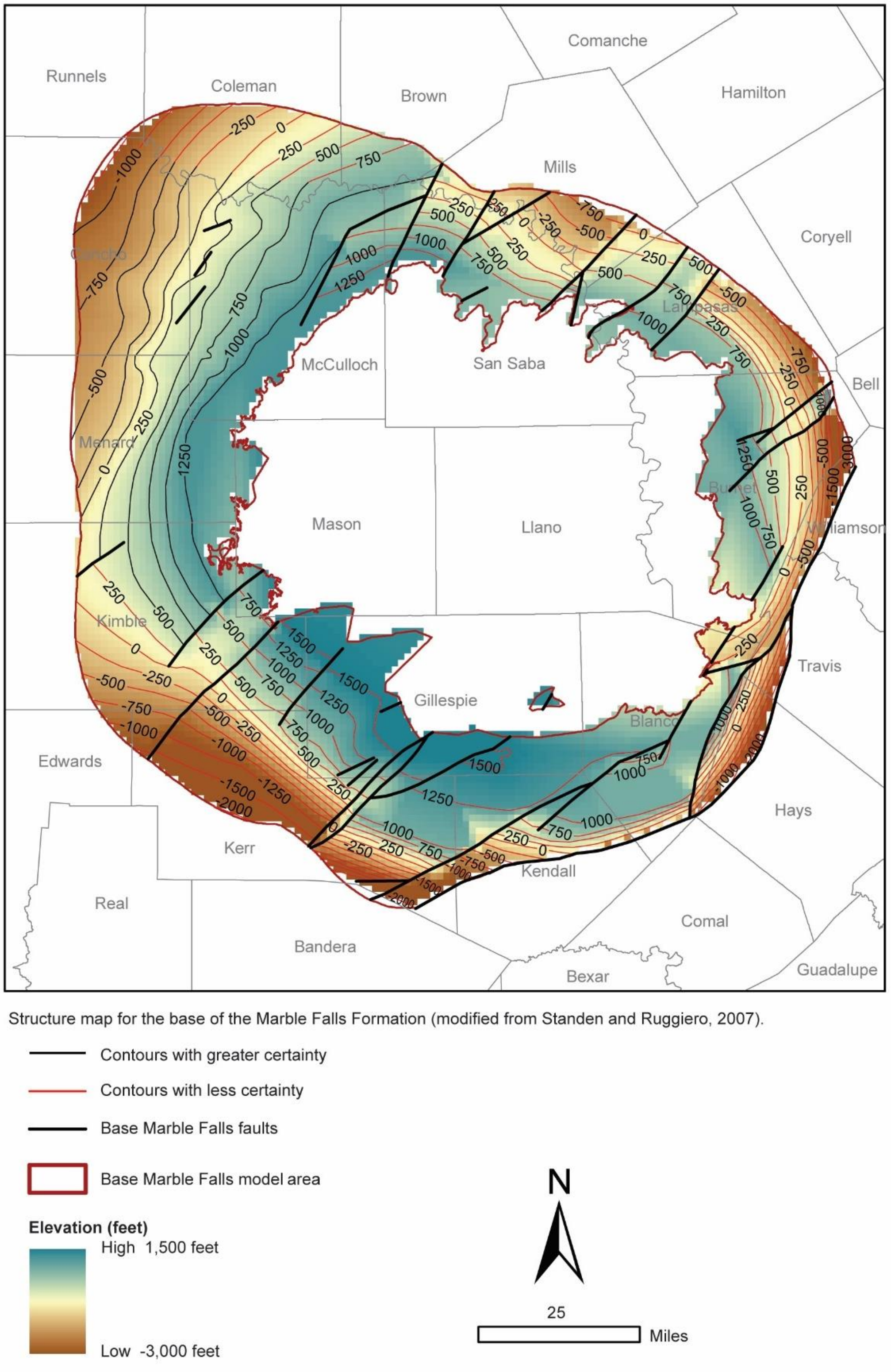


Figure 6-82. Structure map for the base of the Marble Falls Formation (modified from Standen and Ruggiero, 2007).

Flows to surface water and other aquifers

Numerous large springs originate from the Marble Falls Aquifer and provide a significant part of the baseflow to the San Saba River in McCulloch and San Saba counties and to the Colorado River in San Saba and Lampasas counties. Table 6-59 shows a summary of baseflow in the outcrop areas of the Marble Falls Aquifer. Where underlying beds are thin or absent, the Marble Falls Aquifer may be hydraulically connected to the Ellenburger-San Saba Aquifer. Table 6-60 shows groundwater availability model analysis estimates of total flow and average annual flow between the Marble Falls Aquifer and other aquifers.

Table 6-59. Summary of groundwater flow from the Marble Falls Aquifer to surface water, by county.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Burnet	23	1.4	0.3
Kimble	2	0.1	0
Lampasas	20	0.6	0.1
Llano	2	0.1	0
Mason	5	0.1	0
McCulloch	28	0.5	0.1
San Saba	125	3.3	0.7
Total	**205**	**6.1**	**1.2**

Table 6-60. Model estimates of inter-aquifer flows between the Marble Falls Aquifer and other major and minor aquifers.

Flow from	Flow to	Total flow (acre-feet per year)
Marble Falls Aquifer	Ellenburger-San Saba Aquifer	3,647
Edwards-Trinity (Plateau) Aquifer	Marble Falls Aquifer	7
Ellenburger-San Saba Aquifer	Marble Falls Aquifer	2,368
Trinity Aquifer	Marble Falls Aquifer	144

Water quantity

Total storage in the Marble Falls Aquifer is estimated to be about 265,000 acre-feet. Recoverable storage is estimated to be between 25 and 75 of the total, about 66,000 to 198,000 acre-feet (Table 6-61).

Table 6-61. Total estimated recoverable storage in the Marble Falls Aquifer, by county, in acre-feet.

County	Total storage	25 percent of storage	75 percent of storage
Blanco	1,300	325	975
Burnet	38,000	9,500	28,500
Kimble	2,400	600	1,800
Lampasas	39,000	9,750	29,250
Llano	2,100	525	1,575
Mason	5,300	1,325	3,975
McCulloch	33,000	8,250	24,750
San Saba	144,000	36,000	108,000
Total	**265,100**	**66,275**	**198,825**

Water quality

The water quality in the Marble Falls Aquifer is variable, with the total dissolved solids content increasing down-dip to the north, away from the Llano Uplift. Because the limestone beds composing this aquifer are relatively shallow, the aquifer is susceptible to pollution by surface uses and activities. For example, some wells in Blanco County have produced water with high nitrate concentrations. In the subsurface, groundwater becomes highly mineralized; however, the water produced from this aquifer is suitable for most purposes and generally contains less than 1,000 milligrams per liter of total dissolved solids (Figure 6-83).

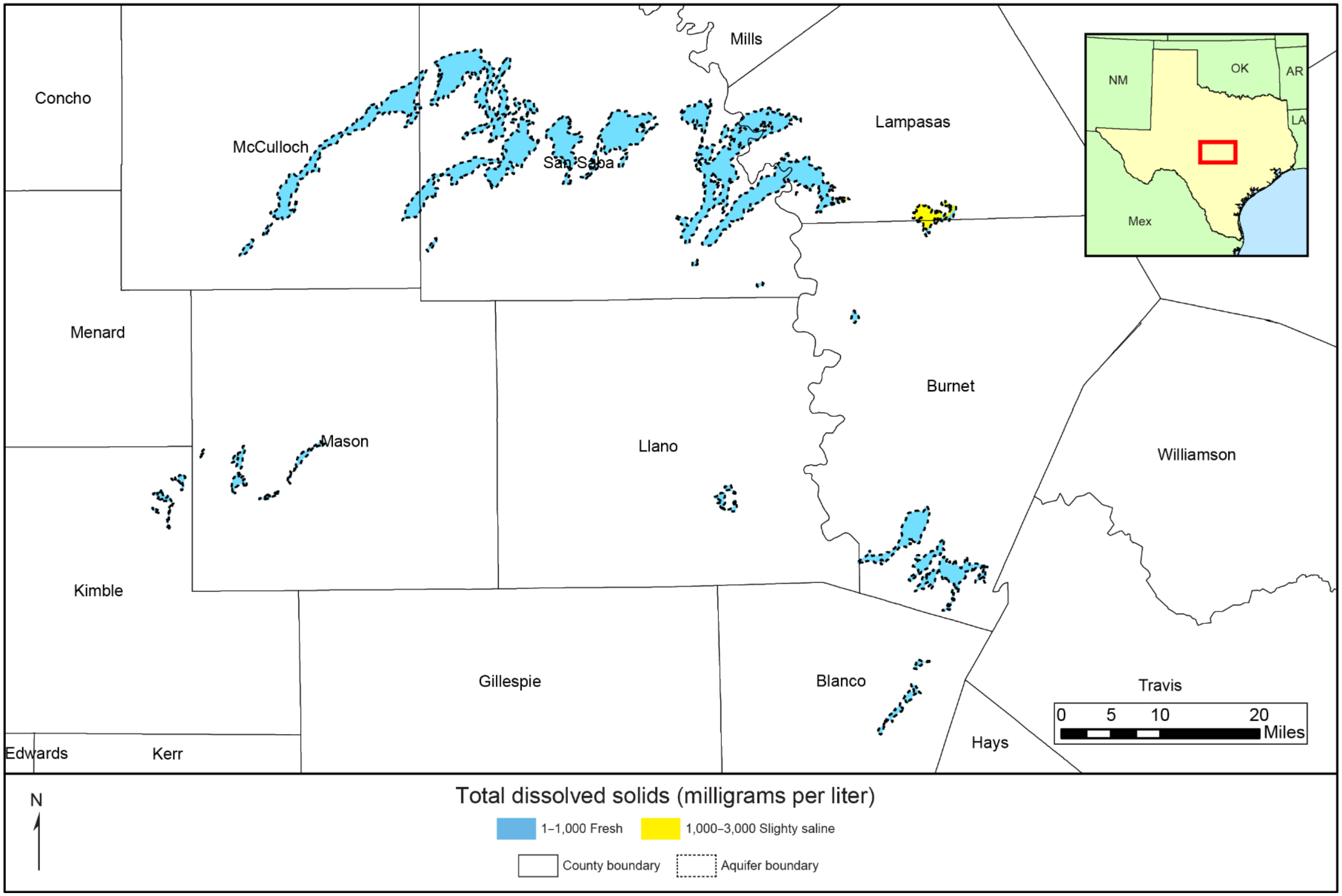


Figure 6-83. **Total dissolved solids in the Marble Falls Aquifer.**

6.23 Nacatoch Aquifer

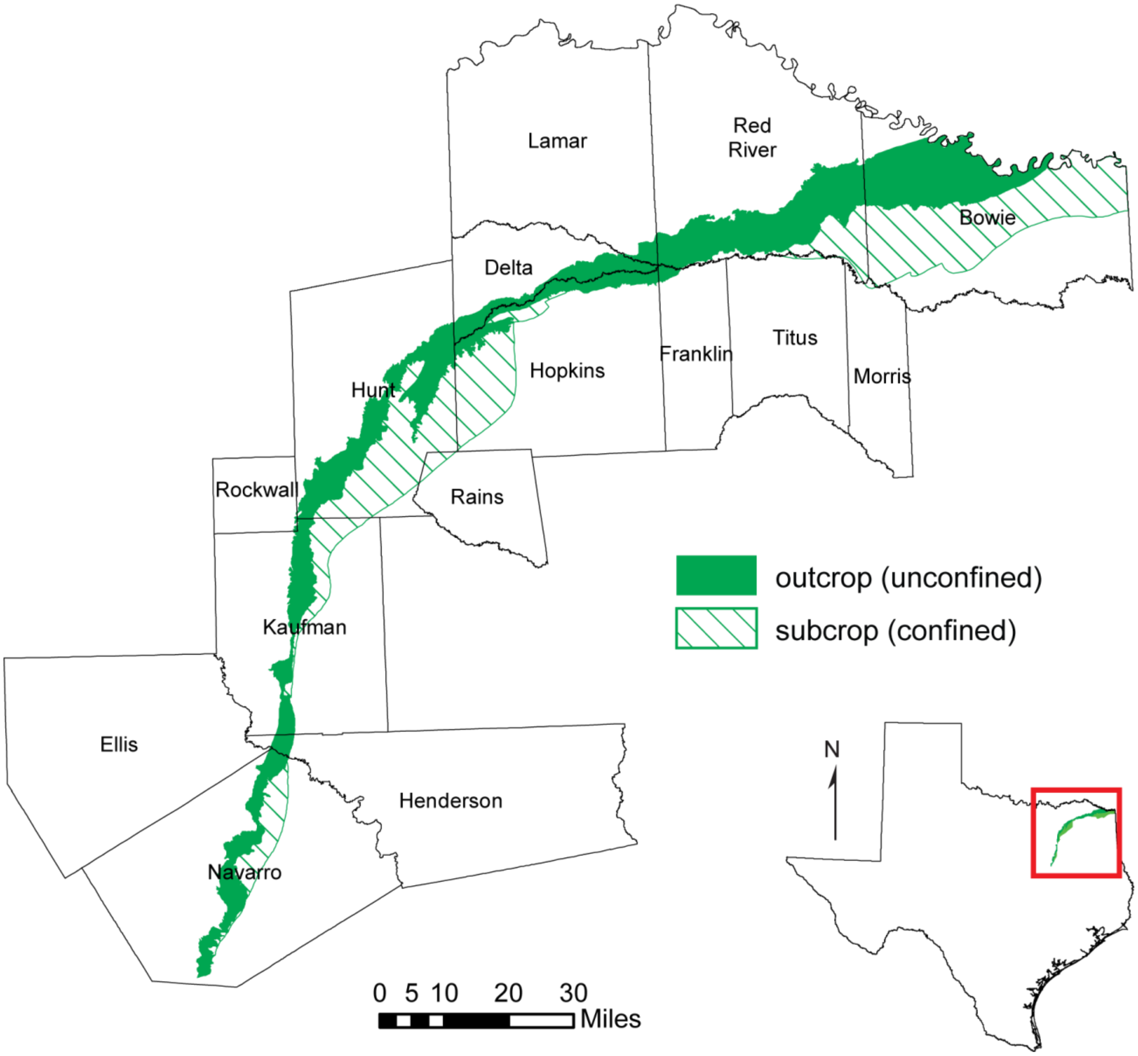


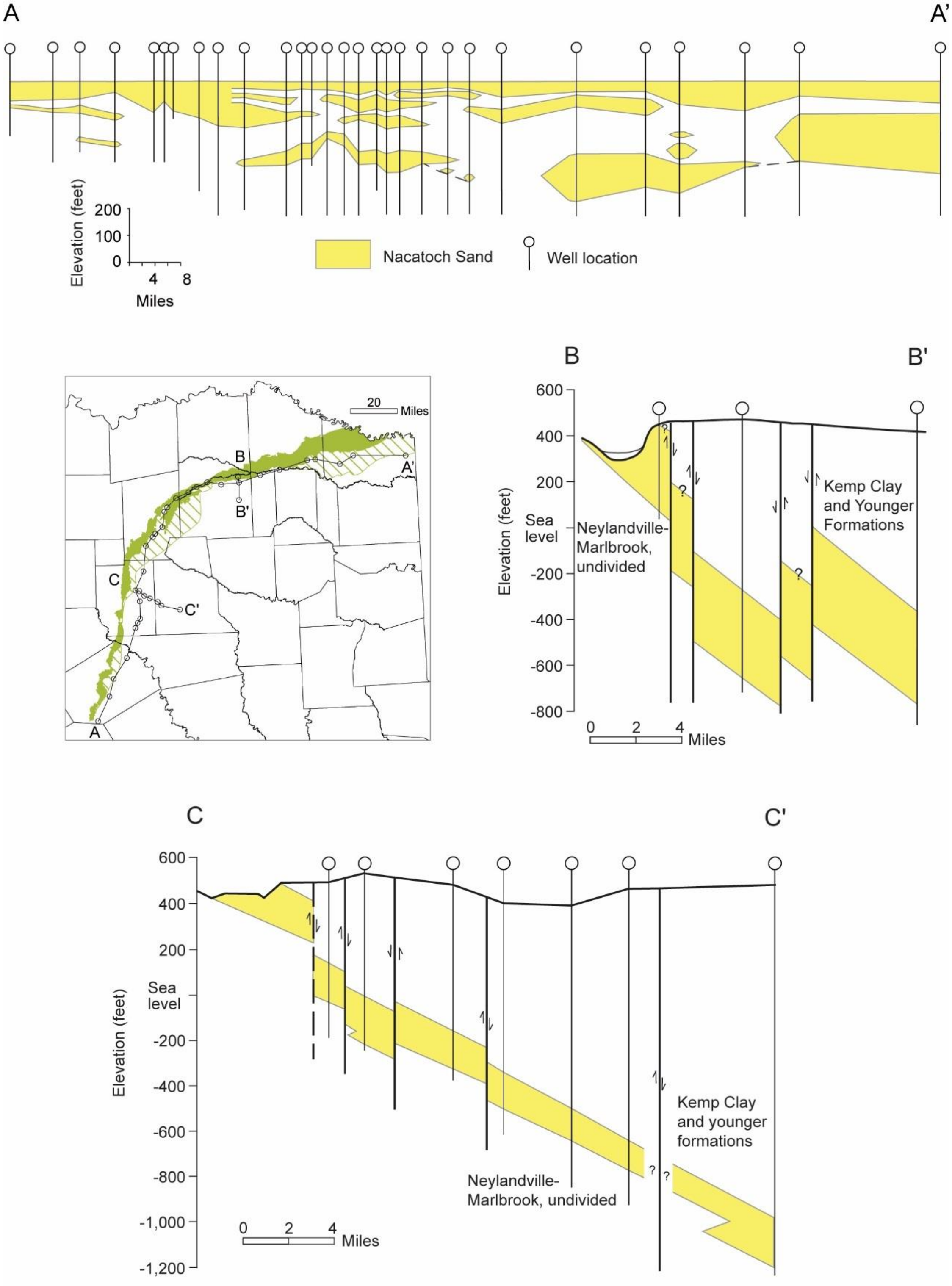
Figure 6-84. Extent of the Nacatoch Aquifer.

Aquifer characteristics

- Aquifer type: confined and unconfined
- Area of outcrop: 891 square miles
- Area in subsurface: 939 square miles
- Proportion of aquifer with groundwater conservation districts: 0.5 percent
- Number of counties containing the aquifer: 15

Geology and hydrogeology

The Nacatoch Aquifer is a minor aquifer that occurs in a narrow band across northeast Texas (Figure 6-84). The aquifer consists of the Nacatoch Sand, which is composed of sequences of sandstone separated by impermeable layers of mudstone or clay (Figure 6-85). These sandstones are marine in origin, coarsen upward, and are laterally discontinuous. The number of sand layers varies throughout the aquifer's extent, and the thickness of individual sand units ranges from more than 100 feet in the north to less than 20 feet to the south. The thickness of intervening mudstone units similarly ranges from more than 100 feet to only a few feet. Freshwater saturated thickness averages about 50 feet. The aquifer also includes a hydraulically connected cover of alluvium that is as much as 80 feet thick along major drainages. Groundwater in this aquifer is usually under artesian conditions except in shallow wells where the Nacatoch Formation crops out and water table conditions exist. The Mexia-Talco Fault Zone generally delineates the subsurface limit of the aquifer.



Modified from Knight (1984); Ashworth (1988)

Figure 6-85. **Structural cross-sections across the Nacatoch Aquifer (modified from Knight, 1984; Ashworth, 1988).**

Flows to surface water and other aquifers

The Nacatoch Aquifer discharges to surface water and springs in the outcrop areas. Some springs fed by the Nacatoch dried up in the 1920s when pumping began in their vicinity, but in other areas of the aquifer where pumping has been minimal, springflow is likely to have been maintained (Beach and others, 2009). Table 6-62 shows a summary of baseflow in the outcrop areas of the Nacatoch Aquifer. Groundwater availability model analysis does not estimate any inter-aquifer flow between the Nacatoch Aquifer and other major and minor aquifers.

Table 6-62. Summary of groundwater flow from the Nacatoch Aquifer to surface water, by county.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Bowie	198	38.3	11.1
Delta	64	3.6	0.2
Ellis	<1	0	0
Franklin	6	0.6	0
Henderson	9	0.6	0.1
Hopkins	61	3.5	0.2
Hunt	155	6.2	0.2
Kaufman	77	6.3	0.6
Lamar	11	1	0.1
Navarro	88	5	0.3
Red River	221	28.5	3.7
Rockwall	1	0.1	0
Titus	<1	0	0
Total	**630**	**94**	**17**

Water quantity

Total storage in the Nacatoch Aquifer is estimated to be more than 4 million acre-feet. Recoverable storage is estimated to be between 25 and 75 percent of the total, or about 1 million to 3 million acre-feet (Table 6-63).

Table 6-63. Total estimated recoverable storage in the Nacatoch Aquifer, by county, in acre-feet.

County	Total storage	25 percent of storage	75 percent of storage
Bowie	240,000	560,000	1,680,000
Delta	100,000	25,000	75,000
Ellis	66	17	50
Franklin	7,300	1,825	5,475
Henderson	9,800	2,450	7,350
Hopkins	330,000	82,500	247,500
Hunt	550,000	137,500	412,500
Kaufman	120,000	30,000	90,000
Lamar	12,000	3,000	9,000
Morris	2,900	725	2,175
Navarro	95,000	23,750	71,250
Rains	18,000	4,500	13,500
Red River	591,000	147,750	443,250
Rockwall	280	70	210
Titus	15,000	3,750	11,250
Total	**4,091,346**	**1,022,837**	**3,068,510**

Water quality

Groundwater in the aquifer is typically alkaline, high in sodium bicarbonate, and soft. Total dissolved solids are significantly higher down-dip south of the Mexia-Talco Fault Zone, where the water contains between 1,000 and 3,000 milligrams per liter of total dissolved solids (Figure 6-86).

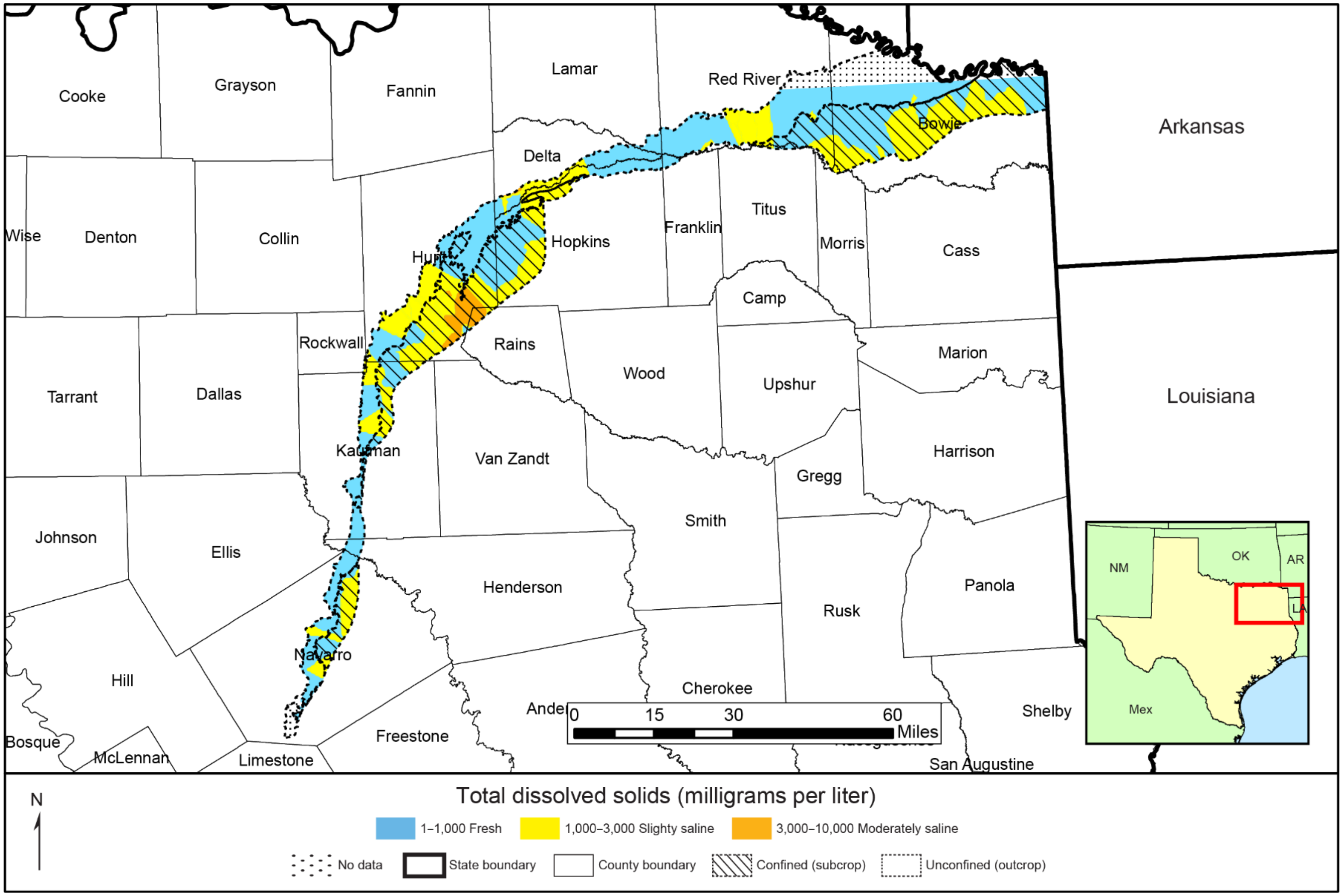


Figure 6-86. **Total dissolved solids in the Nacatoch Aquifer.**

6.24 Queen City Aquifer

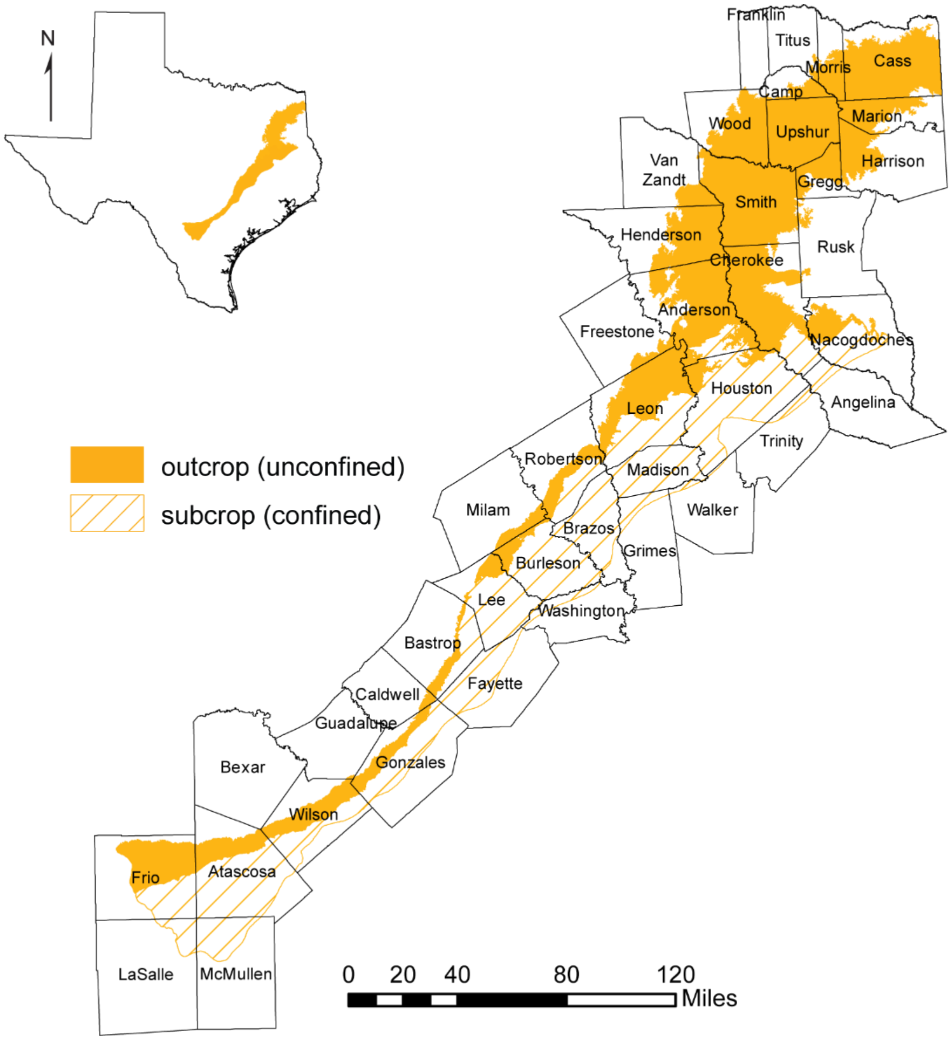


Figure 6-87. Extent of the Queen City Aquifer.

Aquifer characteristics

- Aquifer type: confined and unconfined
- Area of outcrop: 8,781 square miles
- Area in subsurface: 7,015 square miles
- Proportion of aquifer with groundwater conservation districts: 63 percent
- Number of counties containing the aquifer: 42

Geology and hydrogeology

The Queen City Aquifer is a minor, widespread aquifer that stretches across the upper coastal plain of Texas (Figure 6-87). Water is stored in sand, loosely cemented sandstone, and interbedded clay layers of the Queen City Formation, which reaches 2,000 feet in thickness in south Texas (Figure 6-88). The average freshwater saturated thickness of the Queen City Aquifer is about 140 feet.

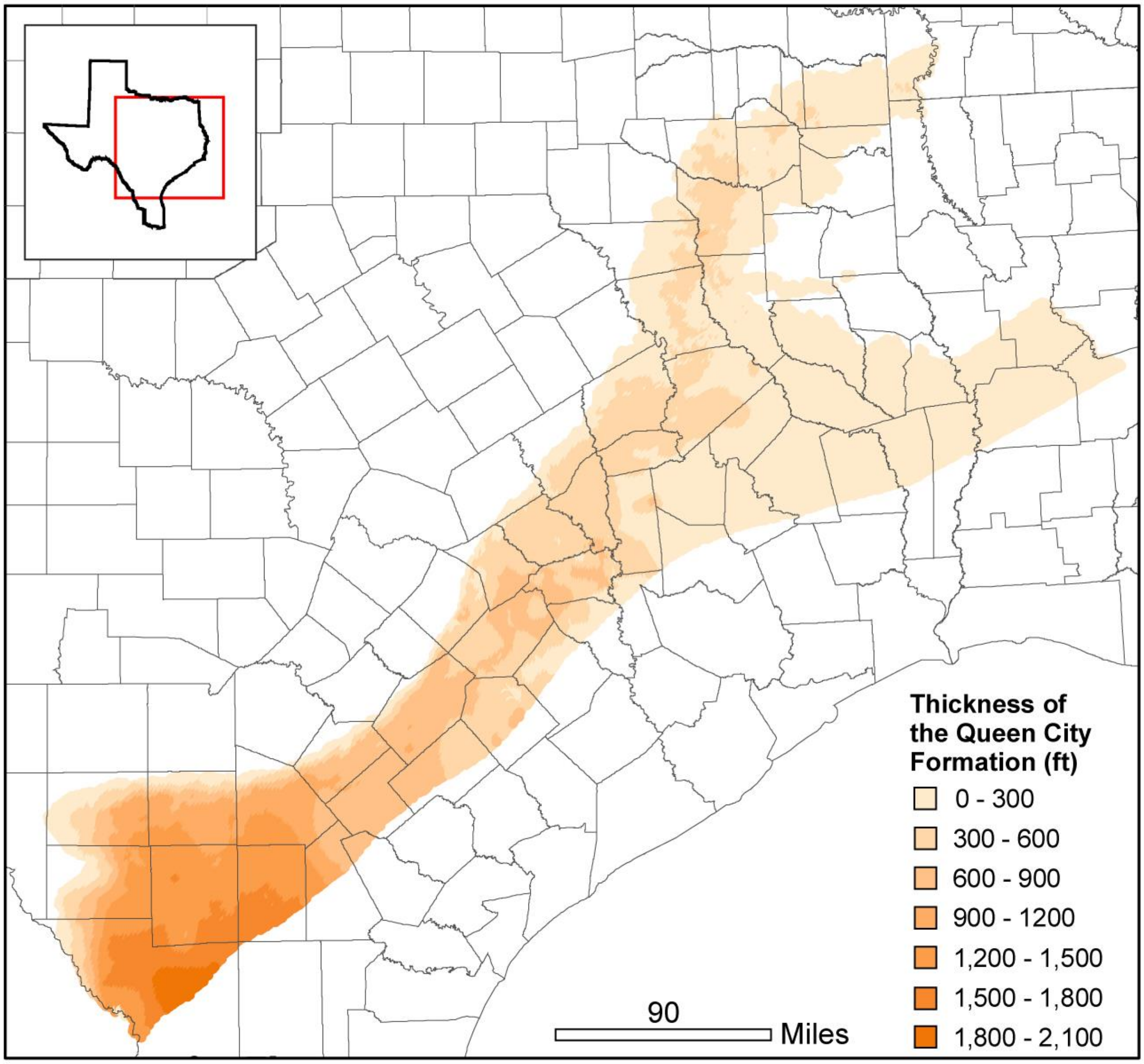


Figure 6-88. Thickness of the Queen City Aquifer (from Kelley and others, 2004).

Flows to surface water and other aquifers

The Queen City Aquifer discharges to streams, springs, and other formations. Table 6-64 shows a summary of baseflow in the outcrop areas of the Queen City Aquifer. Groundwater availability model analysis does not estimate any inter-aquifer flow between the Queen City Aquifer and other major and minor aquifers.

Table 6-64. Summary of groundwater flow from the Queen City Aquifer to surface water, by county.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Anderson	724	108.9	29.8
Atascosa	185	15.5	5.5
Bastrop	83	5.5	1.8
Bexar	0	0	0
Burleson	75	4.1	0.6
Caldwell	21	2.4	0.8
Camp	82	17.8	4
Cass	747	242.3	77.7
Cherokee	668	138.3	42.7
Franklin	1	0.2	0
Freestone	59	6.5	1.4
Frio	381	14.8	4.7
Gonzales	144	13.1	4
Gregg	169	41.8	13.6
Guadalupe	2	0.2	0.1
Harrison	238	66.4	18.1
Henderson	434	46	7.2
Houston	101	19.6	6.3
Lee	65	3.8	0.6
Leon	517	62.4	15.3
Marion	239	77	22.9
Milam	74	4.8	0.7
Morris	133	28	5.7
Nacogdoches	157	47.8	15.6
Robertson	109	6.6	0.6
Rusk	30	10	3.7
Smith	894	202	62

Table 6-64 (continued). Summary of groundwater flow from the Queen City Aquifer to surface water, by county.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Titus	18	3.8	0.6
Upshur	593	150.7	44.6
Van Zandt	102	16.1	3.8
Wilson	227	18.1	6.7
Wood	411	77.2	20
Total	**7,683**	**1,452**	**421**

Water quantity

Total storage in the Queen City Aquifer is estimated to be more than 539 million acre-feet. Recoverable storage is estimated to be between 25 and 75 percent of the total, about 134.8 million to 404.4 million acre-feet (Table 6-65).

Table 6-65. Total estimated recoverable storage in the Queen City Aquifer, by county, in acre-feet.

County	Total storage	25 percent of storage	75 percent of storage
Anderson	19,000,000	4,750,000	14,250,000
Angelina	2,000,000	500,000	1,500,000
Atascosa	83,000,000	20,750,000	62,250,000
Bastrop	9,500,000	2,375,000	7,125,000
Brazos	25,000,000	6,250,000	18,750,000
Burleson	29,000,000	7,250,000	21,750,000
Caldwell	430,000	107,500	322,500
Camp	600,000	150,000	450,000
Cass	8,000,000	2,000,000	6,000,000
Cherokee	15,000,000	3,750,000	11,250,000
Fayette	19,640,000	4,910,000	14,730,000
Freestone	290,000	72,500	217,500
Frio	45,000,000	11,250,000	33,750,000
Gonzales	26,000,000	6,500,000	19,500,000
Gregg	1,500,000	375,000	1,125,000
Grimes	4,970,000	1,242,500	3,727,500

Table 6-65 (continued). Total estimated recoverable storage in the Queen City Aquifer, by county, in acre-feet.

County	Total storage	25 percent of storage	75 percent of storage
Harrison	1,200,000	300,000	900,000
Henderson	6,700,000	1,675,000	5,025,000
Houston	37,000,000	9,250,000	27,750,000
La Salle	15,000,000	3,750,000	11,250,000
Lee	23,000,000	5,750,000	17,250,000
Leon	25,000,000	6,250,000	18,750,000
Madison	20,000,000	5,000,000	15,000,000
Marion	2,500,000	625,000	1,875,000
McMullen	33,000,000	8,250,000	24,750,000
Milam	650,000	162,500	487,500
Morris	1,300,000	325,000	975,000
Nacogdoches	4,500,000	1,125,000	3,375,000
Robertson	8,800,000	2,200,000	6,600,000
Rusk	58,000	14,500	43,500
Smith	23,000,000	5,750,000	17,250,000
Titus	63,000	15,750	47,250
Trinity	1,900,000	475,000	1,425,000
Upshur	7,800,000	1,950,000	5,850,000
Van Zandt	1,200,000	300,000	900,000
Walker	624,000	156,000	468,000
Washington	4,330,000	1,082,500	3,247,500
Wilson	24,000,000	6,000,000	18,000,000
Wood	8,700,000	2,175,000	6,525,000
Total	**539,257,800**	**134,814,450**	**404,443,350**

Water quality

Groundwater in the Queen City Aquifer is generally fresh, with an average of about 300 milligrams per liter total dissolved solids in the recharge zone and about 750 milligrams per liter deeper in the aquifer (Figure 6-89). Although salinity decreases from south to north, areas of excessive iron concentration and high acidity occur in the northeast.

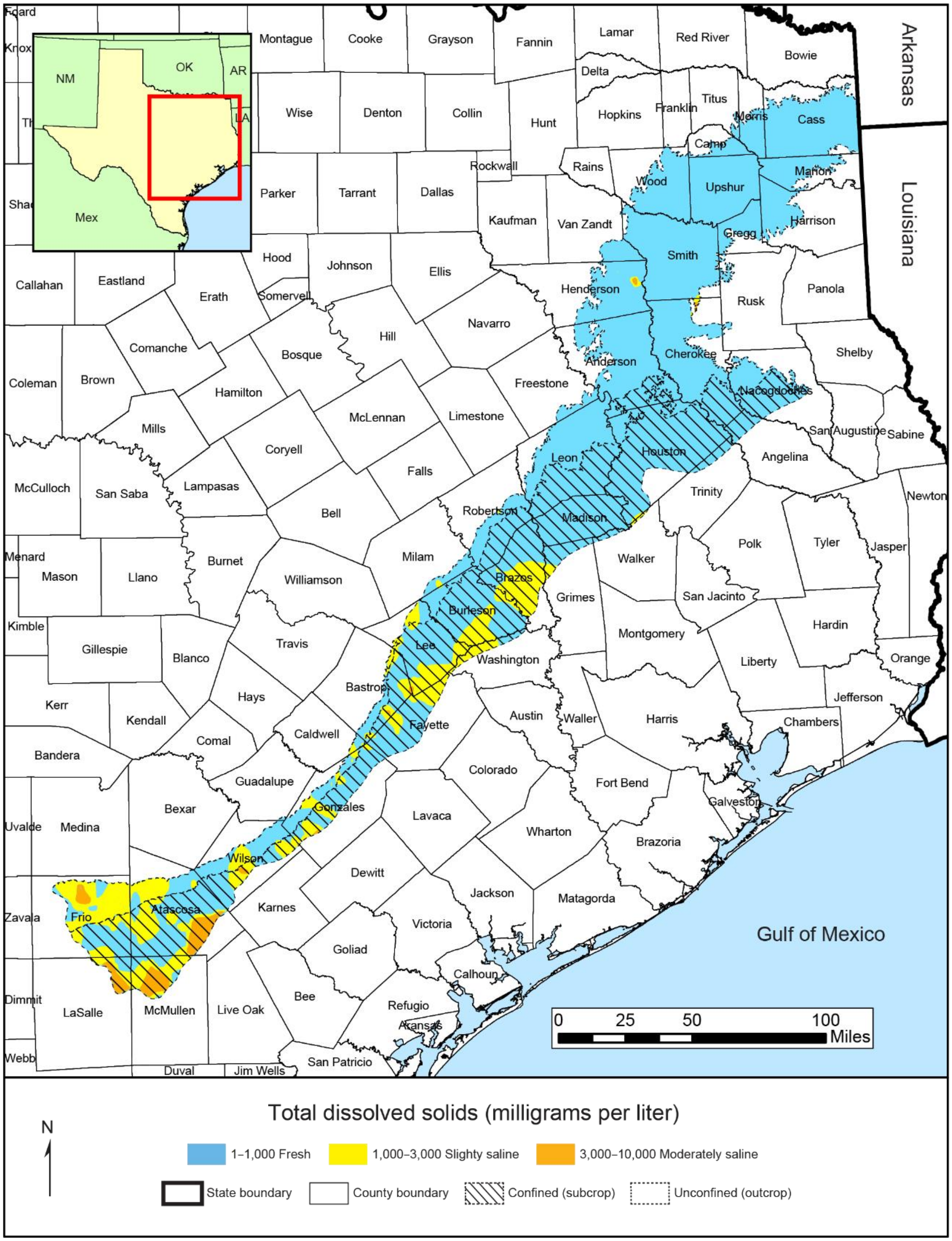


Figure 6-89. Total dissolved solids in the Queen City Aquifer.

6.25 Rita Blanca Aquifer

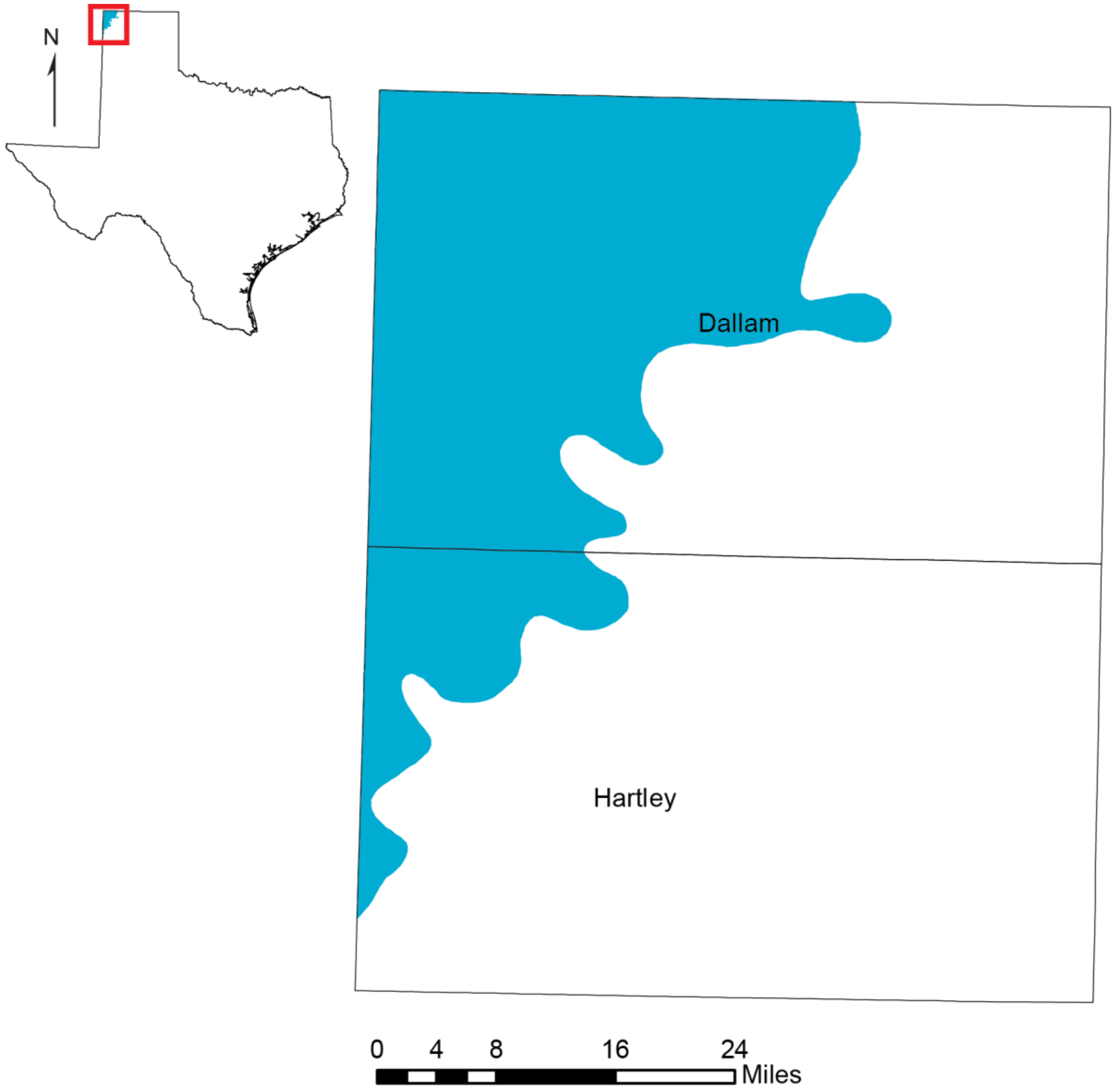


Figure 6-90. Extent of the Rita Blanca Aquifer.

Aquifer characteristics

- Aquifer type: mostly confined
- Area of aquifer: 918 square miles
- Proportion of aquifer with groundwater conservation districts: 99 percent
- Number of counties containing the aquifer: 2

Geology and hydrogeology

The Rita Blanca Aquifer is a minor aquifer that underlies the Ogallala Aquifer in the northwest corner of the Texas Panhandle (Figure 6-90) and extends into New Mexico and Oklahoma. Groundwater occurs in the coarse-grained sand and gravel layers of the Lytle and Dakota formations, as well as in the Exeter Sandstone and the Morrison Formation (Figure 6-91). The thickness of the aquifer is as much as 250 feet, and freshwater saturated thickness averages about 180 feet. Groundwater in the Rita Blanca Aquifer is generally under confined conditions in Texas. In some places, the Rita Blanca Aquifer is hydraulically connected to the Ogallala Aquifer and the underlying Dockum Aquifer. The total thickness of water-bearing rocks in these places is much greater.

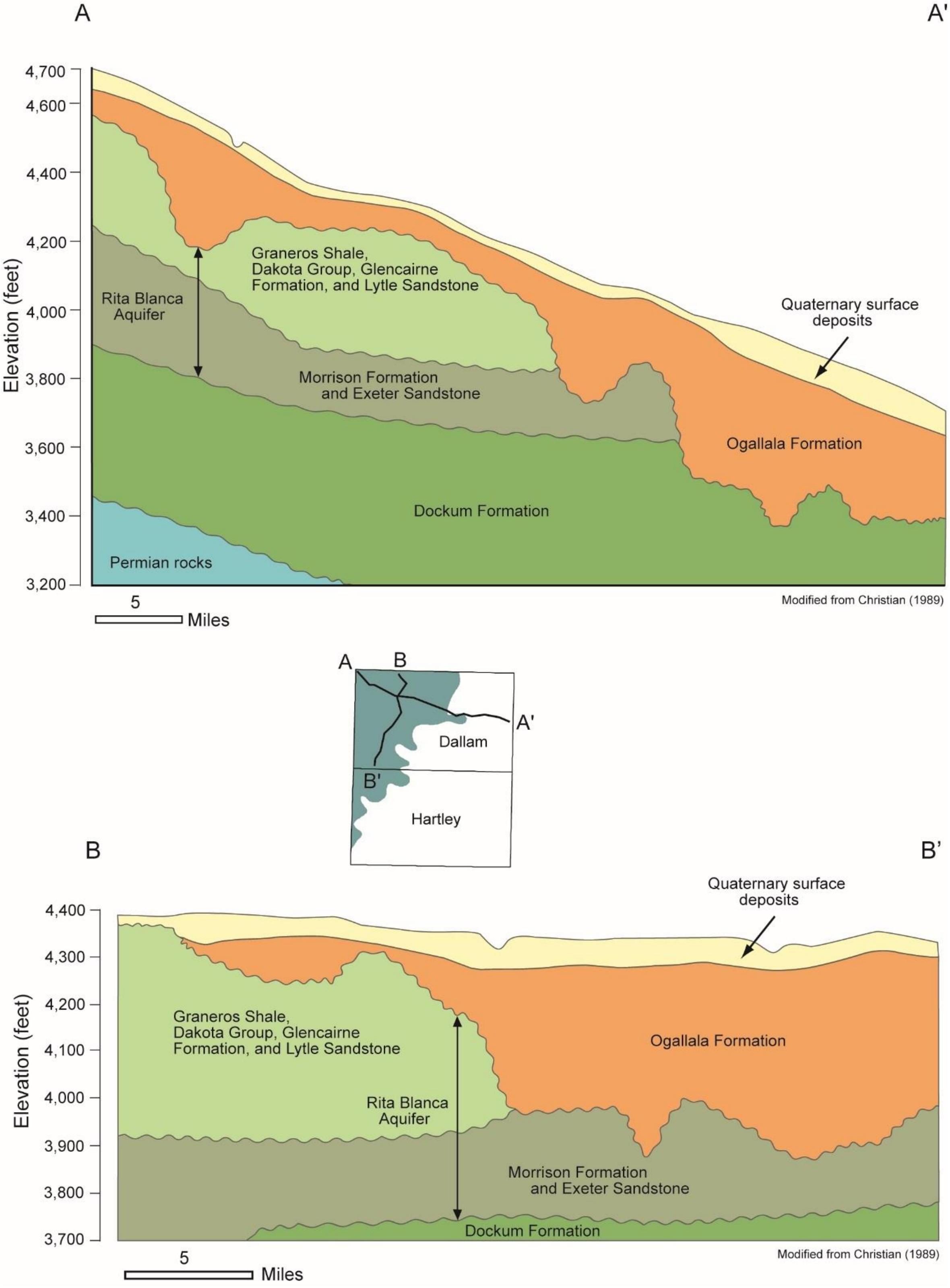


Figure 6-91. Geologic cross-section of the Rita Blanca Aquifer (modified from Christian, 1989).

Flows to surface water and other aquifers

The Rita Blanca Aquifer does not have any outcrop area in Texas and consequently there is no direct flow between the Rita Blanca Aquifer and surface-water bodies. Table 6-66 shows groundwater availability model estimates of total flow and average annual flow between the Rita Blanca Aquifer and other aquifers.

Table 6-66. Model estimates of inter-aquifer flows between the Rita Blanca Aquifer and other major and minor aquifers.

Flow from	Flow to	Total flow (acre-feet per year)
Rita Blanca Aquifer	Dockum Aquifer	83
Dockum Aquifer	Rita Blanca Aquifer	115
Ogallala Aquifer	Rita Blanca Aquifer	1,670

Water quantity

Total storage in the Rita Blanca Aquifer is estimated to be about 11.1 million acre-feet. Recoverable storage is estimated to be between 25 and 75 of the total, about 2.7 million to 8.3 million acre-feet (Table 6-67).

Table 6-67. Total estimated recoverable storage in the Rita Blanca Aquifer, by county, in acre-feet.

County	Total storage	25 percent of storage	75 percent of storage
Dallam	9,800,000	2,450,000	7,350,000
Hartley	1,300,000	325,000	975,000
Total	**11,100,000**	**2,775,000**	**8,325,000**

Water quality

Water in the Rita Blanca Aquifer is usually fresh, containing less than 1,000 milligrams per liter of total dissolved solids, but very hard; however, some parts of the aquifer produce water that is slightly saline, containing more than 1,000 milligrams per liter of total dissolved solids (Figure 6-92). Primary and secondary maximum contaminant level exceedances for gross alpha radiation, arsenic, fluoride, and total dissolved solids occur in a small percentage of wells completed in the Rita Blanca (Reedy and others, 2011).

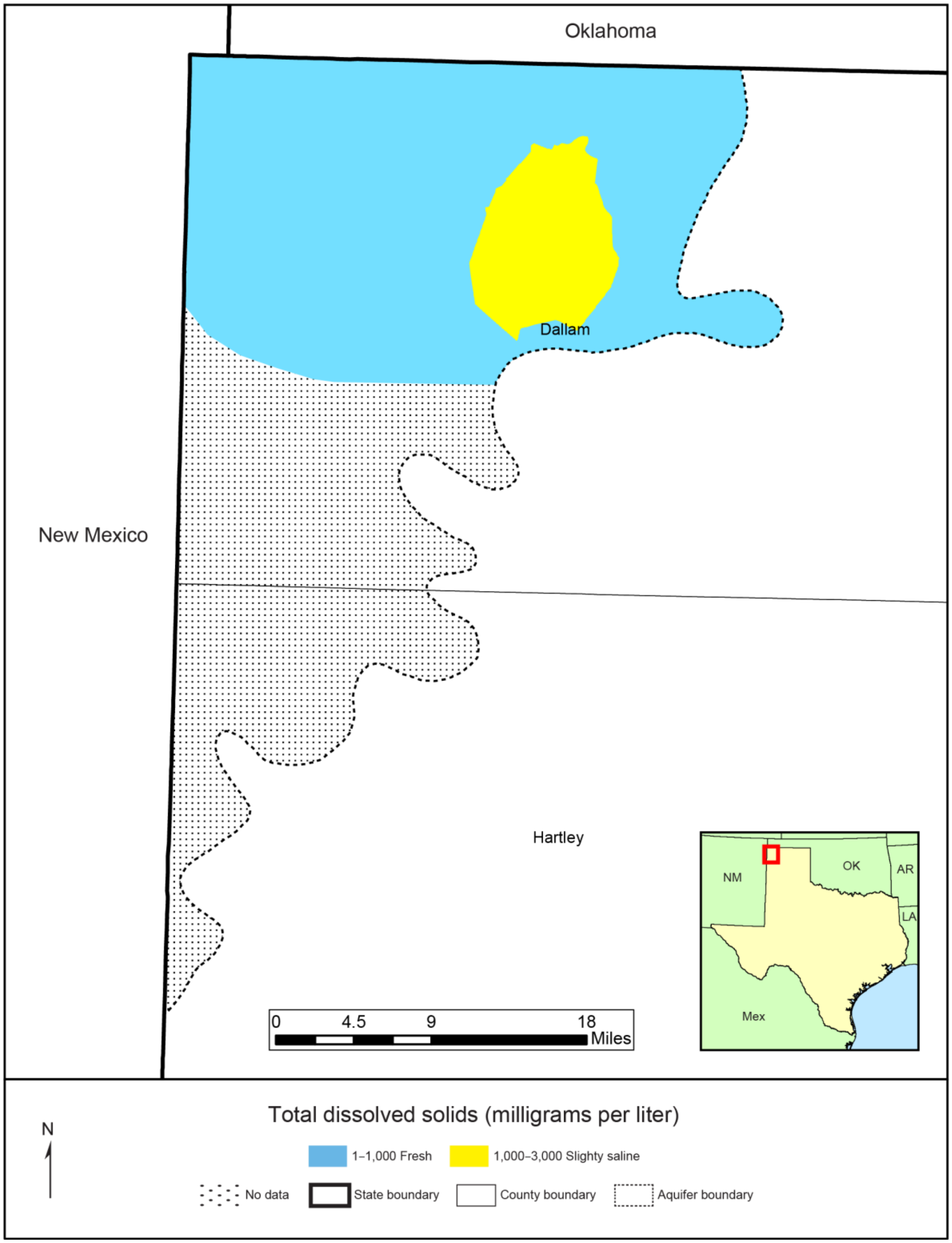


Figure 6-92. Total dissolved solids in the Rita Blanca Aquifer.

6.26 Rustler Aquifer

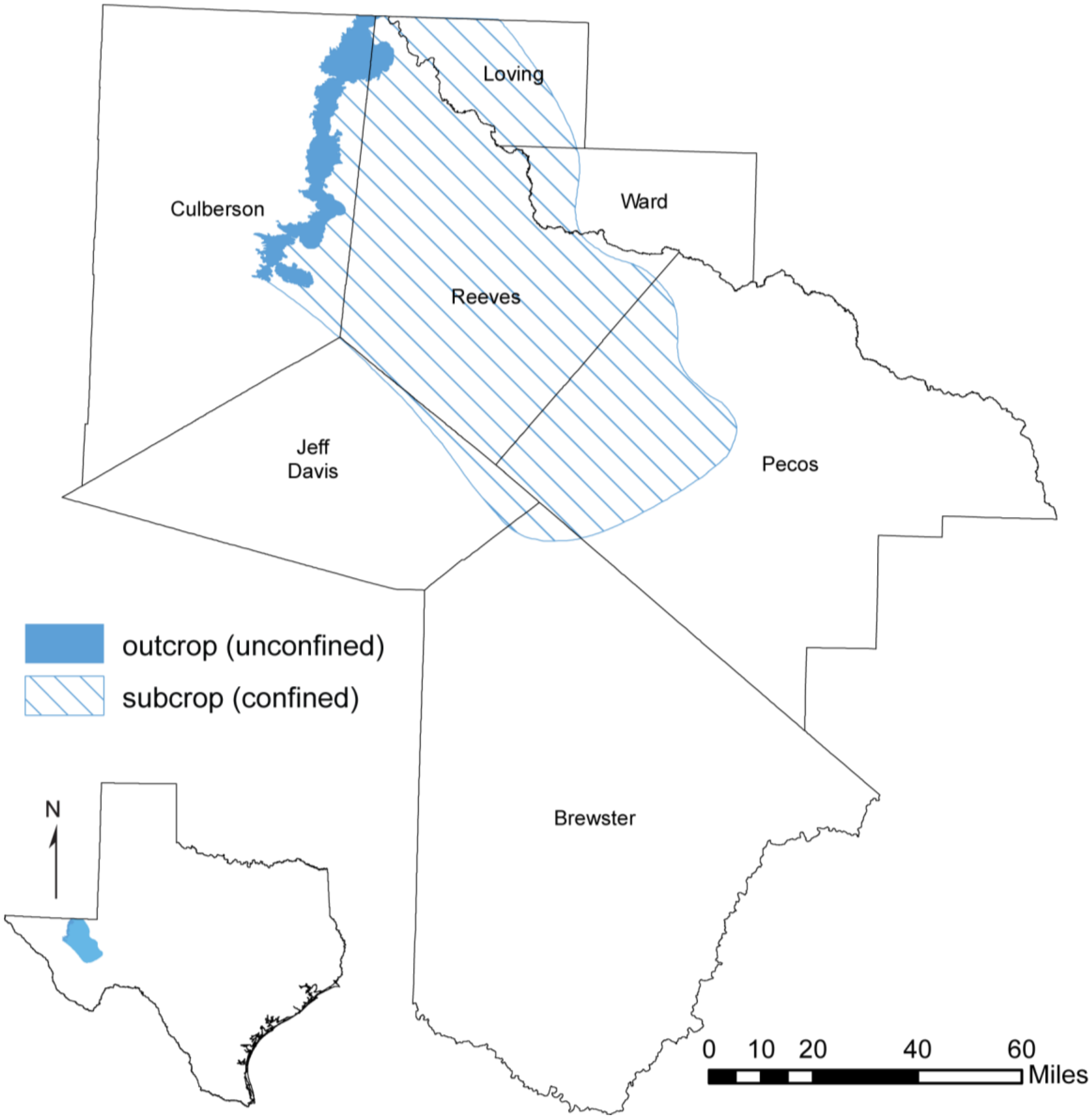


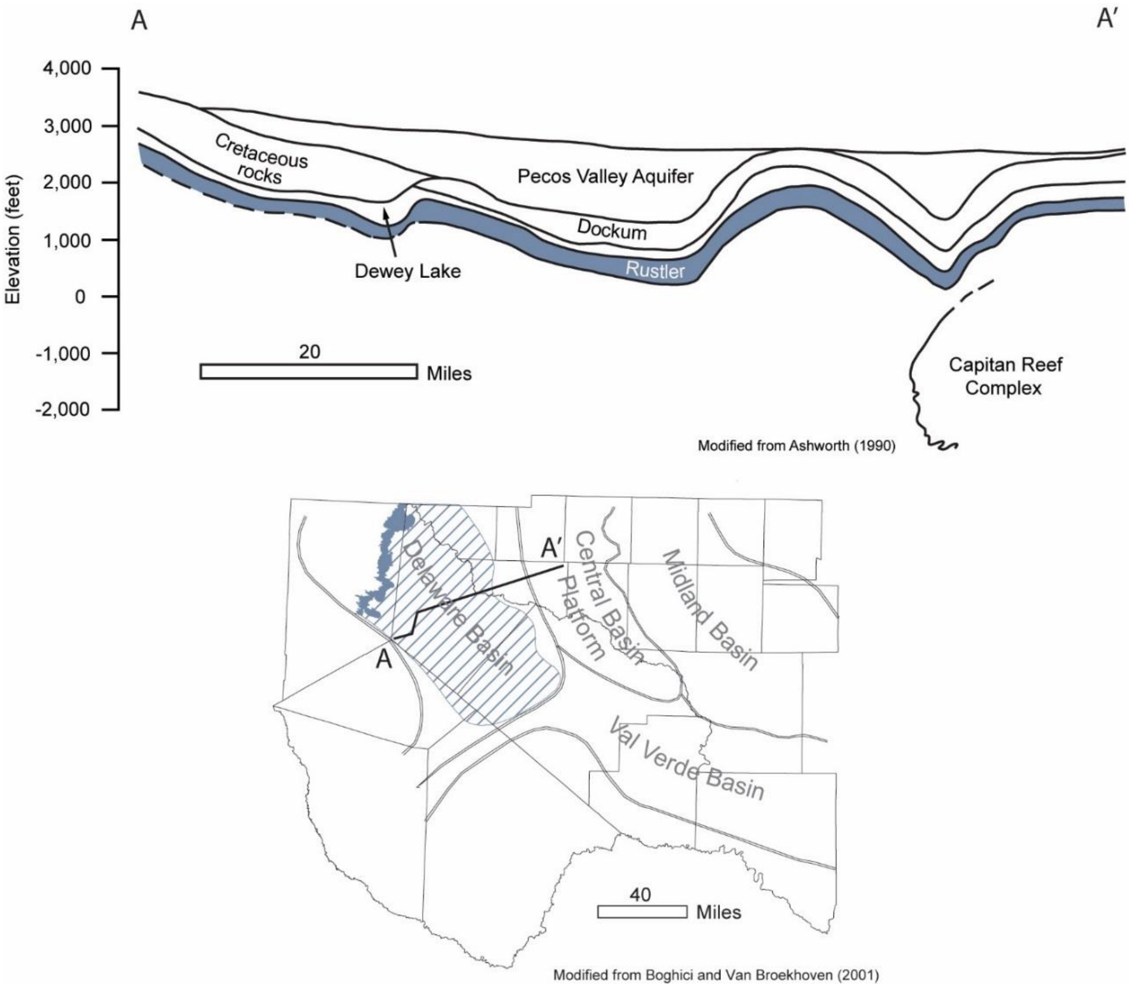
Figure 6-93. Extent of the Rustler Aquifer.

Aquifer characteristics

- Aquifer type: confined and unconfined
- Area of outcrop: 311 square miles
- Area in subsurface: 4,881 square miles
- Proportion of aquifer with groundwater conservation districts: 76 percent
- Number of counties containing the aquifer: 7

Geology and hydrogeology

The Rustler Aquifer is a minor aquifer located in Brewster, Culberson, Jeff Davis, Loving, Pecos, Reeves, and Ward counties (Figure 6-93). The aquifer consists of the carbonates and evaporites of the Rustler Formation, which is the youngest unit of the Late Permian Ochoan Series. The Rustler Formation is 250 to 670 feet thick and extends down-dip into the subsurface toward the center of the Delaware Basin to the east (Figure 6-94). It becomes thinner along the eastern margin of the Delaware Basin and across the Central Basin Platform and Val Verde Basin. There it conformably overlies the Salado Formation. Groundwater occurs in partly dissolved dolomite, limestone, and gypsum. Most of the water production comes from fractures and solution openings in the upper part of the formation.



Modified from Ashworth (1990)

Modified from Boghici and Van Broekhoven (2001)

Figure 6-94. Geologic cross-section of the Rustler Aquifer. The index map shows the major structures in the region (modified from Ashworth, 1990; Boghici and Van Broekhoven, 2001).

Flows to surface water and other aquifers

The Rustler Aquifer only in outcrops in Culberson and Reeves Counties and has limited discharge to surface water in the area. Results of the baseflow analysis for the Rustler Aquifer are shown in Table 6-68. Table 6-69 shows groundwater availability model estimates of total flow and average annual flow between the Rustler Aquifer and other aquifers.

Table 6-68. Summary of groundwater flow from the Rustler Aquifer to surface water.

County	Area of aquifer Outcrop in county (square miles)	Sum of average Annual baseflow (cubic feet per second)	Sum of median Annual baseflow (cubic feet per second)
Culberson	289	1.9	0.7
Reeves	24	0.1	0
Total	**313**	**2**	**0.7**

Table 6-69. Model estimates of inter-aquifer flows between the Rustler and Dockum aquifers.

Flow from	Flow to	Total flow (acre-feet per year)	Average annual (net, acre-feet)
Rustler Aquifer	Dockum Aquifer	1	1

Water quantity

Total storage in the Rustler Aquifer is estimated to be nearly 37 million acre-feet. Recoverable storage is estimated to be between 25 and 75 of the total, or about 9.2 million to 27.6 million acre-feet (Table 6-70).

Table 6-70. Total estimated recoverable storage in the Rustler Aquifer, by county, in acre-feet.

County	Total storage	25 percent of storage	75 percent of storage
Brewster	53,000	13,250	39,750
Culberson	4,200,000	1,050,000	3,150,000
Jeff Davis	670,000	167,500	502,500
Loving	3,400,000	850,000	2,550,000
Pecos	8,600,000	2,150,000	6,450,000
Reeves	19,000,000	4,750,000	14,250,000
Ward	980,000	245,000	735,000
Total	**36,903,000**	**9,225,750**	**27,677,250**

Water quality

Although some parts of the aquifer produce freshwater containing less than 1,000 milligrams per liter of total dissolved solids, the water is generally slightly to moderately saline and contains total dissolved solids between 1,000 and 4,600 milligrams per liter (Figure 6-95).

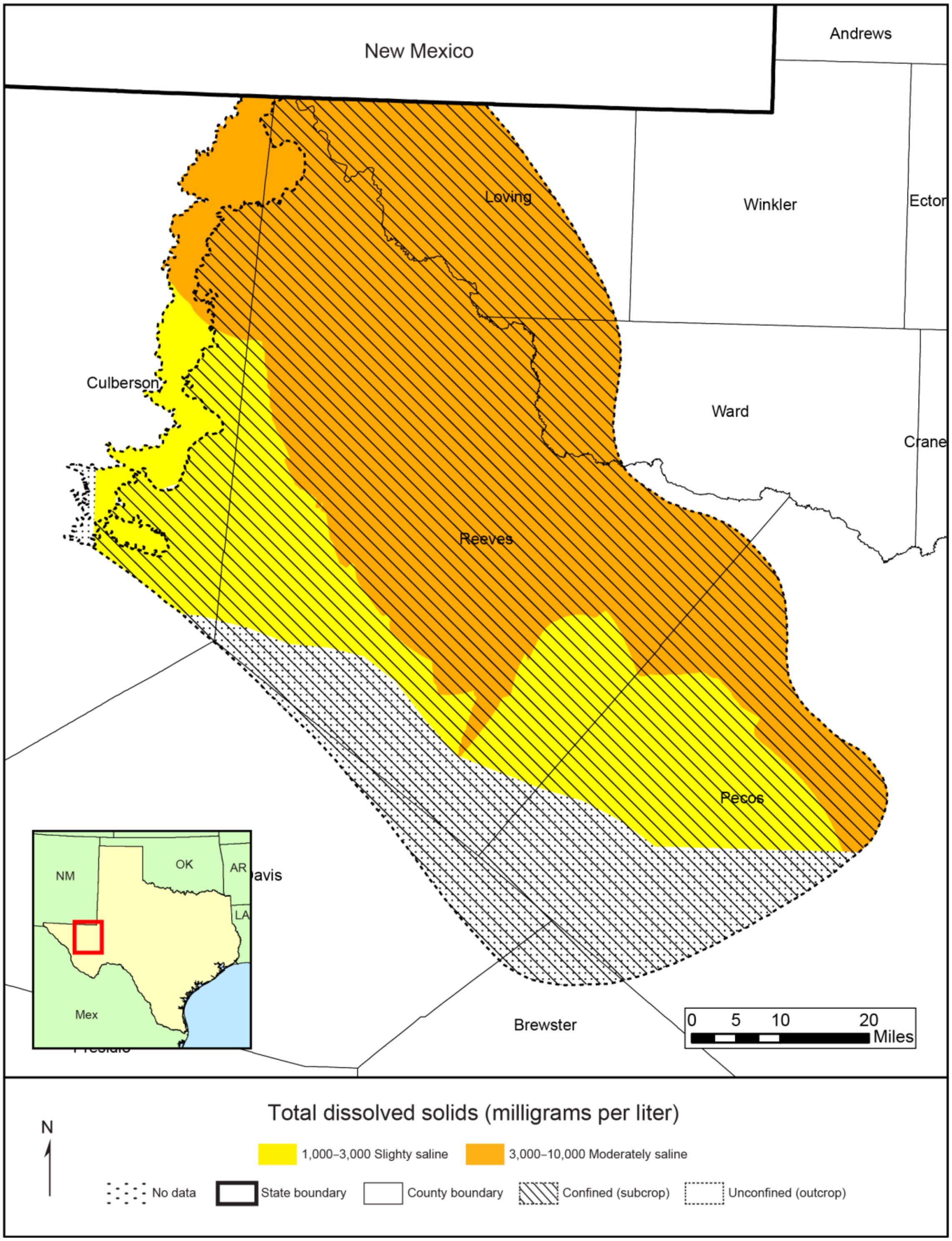


Figure 6-95. Total dissolved solids in the Rustler Aquifer.

6.27 Sparta Aquifer

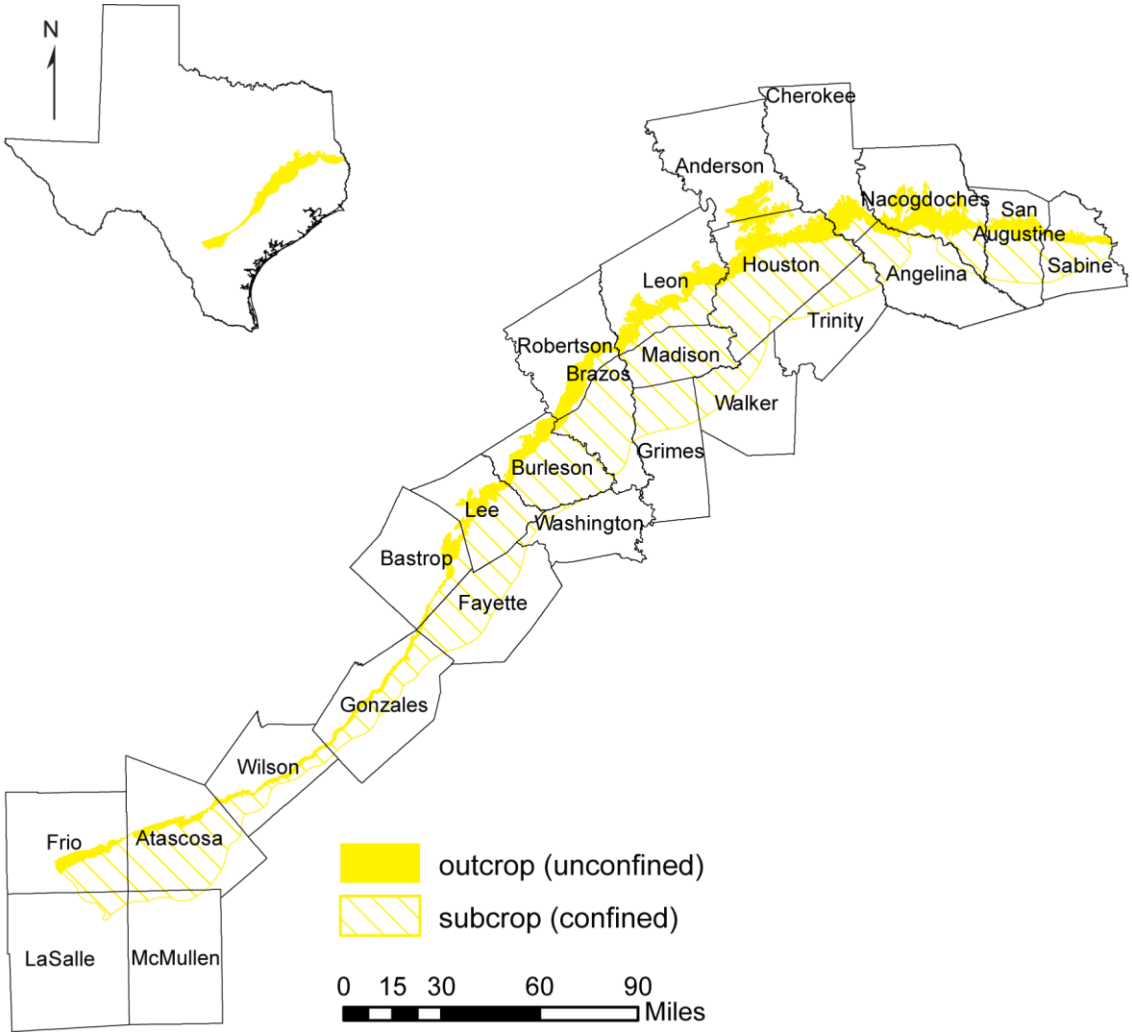


Figure 6-96. Extent of the Sparta Aquifer.

Aquifer characteristics

- Aquifer type: confined and unconfined
- Area of outcrop: 1,549 square miles
- Area in subsurface: 6,321 square miles
- Proportion of aquifer with groundwater conservation districts: 76 percent
- Number of counties containing the aquifer: 25

Geology and hydrogeology

The Sparta Aquifer is a minor aquifer extending across east and south Texas, parallel to the Gulf of Mexico coastline and about 100 miles inland (Figure 6-96). Water is contained within a part of the Claiborne Group known as the Sparta Formation, a sand-rich unit interbedded with silt and clay layers and with massive sand beds in the bottom section. The thickness of the formation changes gradually from more than 700 feet at the Sabine River to about 200 feet in south Texas. Freshwater saturated thickness averages about 120 feet (Figure 6-97).

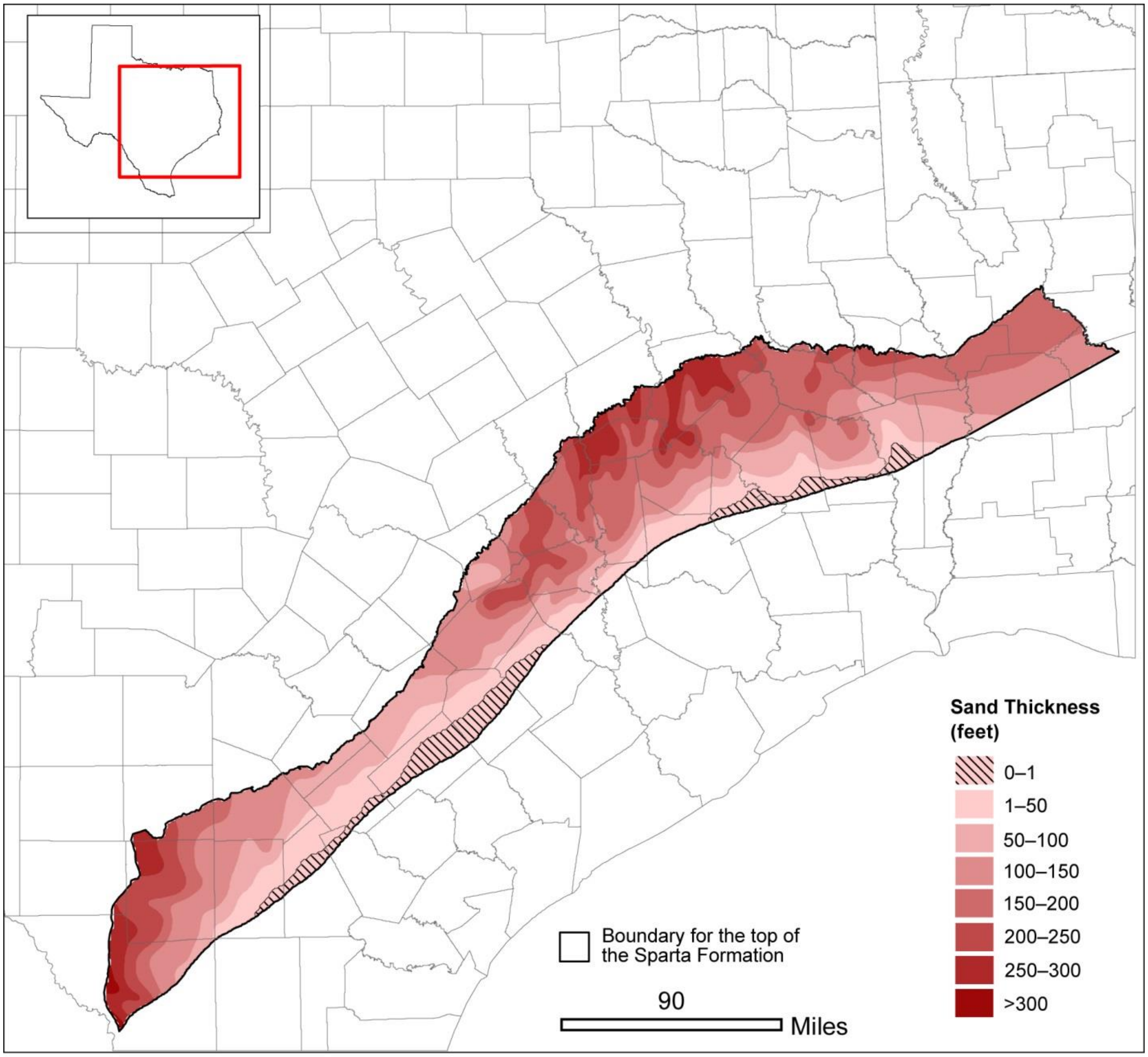


Figure 6-97. Total sand thickness in the Sparta Aquifer (modified from Ricoy and Brown, 1977; Kelley and others, 2004).

Flows to surface water and other aquifers

Groundwater from the Sparta Aquifer discharges to streams, springs, and other formations. Table 6-71 shows a summary of baseflow in the outcrop areas of the Sparta Aquifer. Groundwater availability model analysis does not estimate any inter-aquifer flow between the Sparta Aquifer and other major and minor aquifers.

Table 6-71. Summary of groundwater flow from the Sparta Aquifer to surface water, by county.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Anderson	94	20.2	6.4
Angelina	20	6.4	2.2
Atascosa	49	3.3	1.2
Bastrop	62	3.1	0.8
Burleson	83	4.7	0.7
Cherokee	86	27.3	10.3
Fayette	3	0.3	0.1
Frio	60	1.3	0.4
Gonzales	47	4.6	1.4
Houston	238	59.8	21.2
Lee	79	3.8	0.6
Leon	202	20.4	4.3
Nacogdoches	223	66.5	17.9
Robertson	105	5.7	0.6
Sabine	47	10.7	2.2
San Augustine	77	20.3	4.9
Wilson	39	3.1	1.1
Total	**1,514**	**262**	**76**

Water quantity

Total storage in the Sparta Aquifer is estimated to be more than 185 million acre-feet. Recoverable storage is estimated to be between 25 and 75 percent of the total, or about 46.4 million to 139.2 million acre-feet (Table 6-72).

Table 6-72. Total estimated recoverable storage in the Sparta Aquifer, by county, in acre-feet.

County	Total storage	25 percent of storage	75 percent of storage
Anderson	640,000	160,000	480,000
Angelina	5,200,000	1,300,000	3,900,000
Atascosa	12,000,000	3,000,000	9,000,000
Bastrop	2,500,000	625,000	1,875,000
Brazos	17,000,000	4,250,000	12,750,000
Burleson	16,000,000	4,000,000	12,000,000
Cherokee	1,700,000	425,000	1,275,000
Fayette	14,900,000	3,725,000	11,175,000
Frio	2,600,000	650,000	1,950,000
Gonzales	5,600,000	1,400,000	4,200,000
Grimes	11,600,000	2,900,000	8,700,000
Houston	25,000,000	6,250,000	18,750,000
La Salle	1,600,000	400,000	1,200,000
Lee	10,000,000	2,500,000	7,500,000
Leon	4,600,000	1,150,000	3,450,000
Madison	16,000,000	4,000,000	12,000,000
McMullen	1,700,000	425,000	1,275,000
Nacogdoches	3,900,000	975,000	2,925,000
Robertson	1,300,000	325,000	975,000
Sabine	6,000,000	1,500,000	4,500,000
San Augustine	6,800,000	1,700,000	5,100,000
Trinity	6,100,000	1,525,000	4,575,000
Walker	8,550,000	2,137,500	6,412,500
Washington	1,860,000	465,000	1,395,000
Wilson	2,500,000	625,000	1,875,000
Total	**185,650,000**	**46,412,500**	**139,237,500**

Water quality

In outcrop areas of the Sparta Aquifer and for a few miles down-dip in the subsurface, the water is usually fresh, with an average concentration of 300 milligrams per liter of total dissolved solids. Water quality deteriorates with depth (below about 2,000 feet), where groundwater has an average concentration of 800 milligrams per liter of total dissolved solids (Figure 6-98). Excessive iron concentrations are common throughout the aquifer.

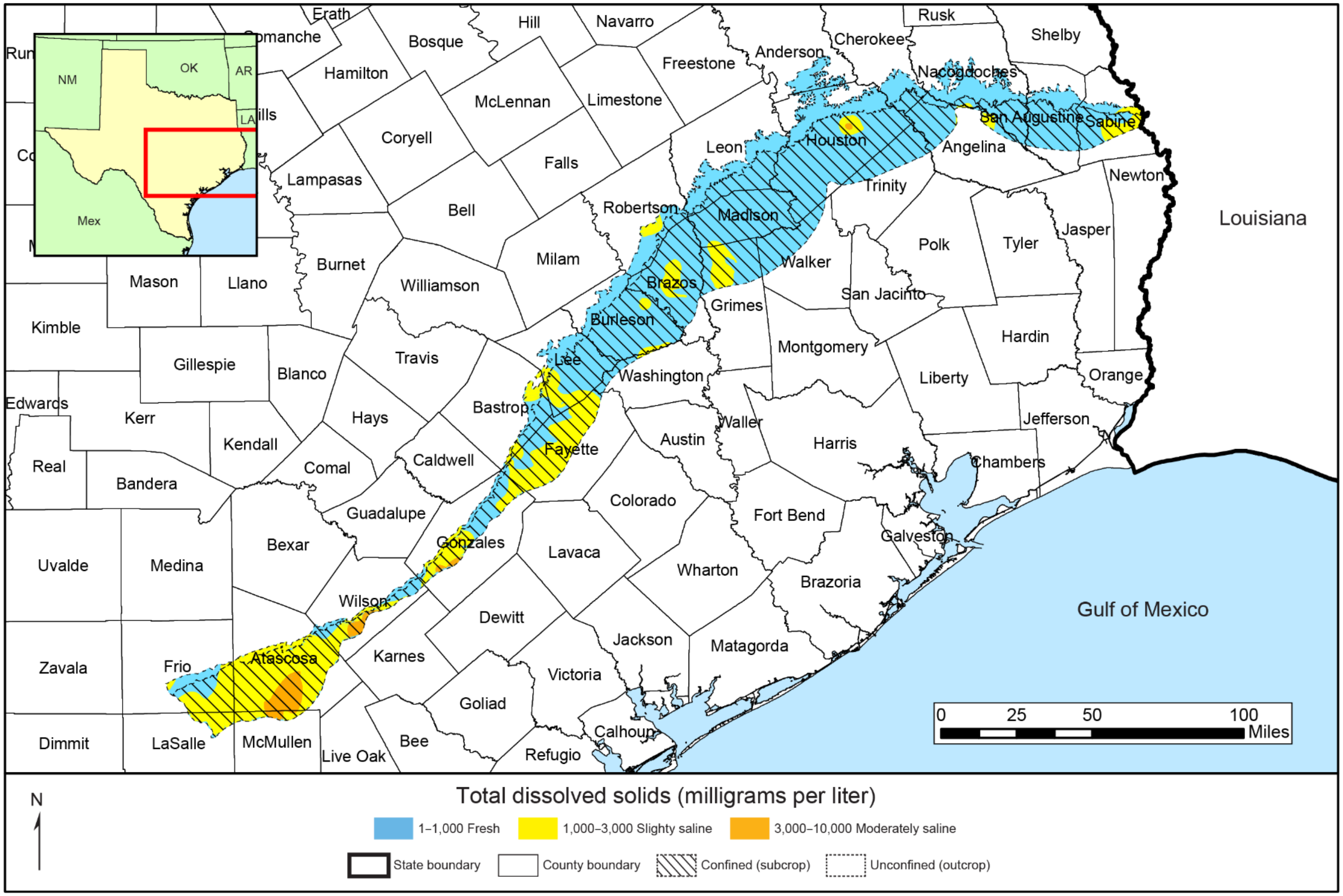


Figure 6-98. Total dissolved solids in the Sparta Aquifer.

6.28 West Texas Bolsons Aquifer

Figure 6-99. Extent of the West Texas Bolsons Aquifer.

Aquifer characteristics

- Aquifer type: unconfined
- Area of aquifer: 1,898 square miles
- Proportion of aquifer with groundwater conservation districts: 81 percent
- Number of counties containing the aquifer: 4

Geology and hydrogeology

The West Texas Bolsons Aquifer is a minor aquifer located in several basins, or bolsons, in far west Texas (Figure 6-99). The aquifer occurs as water-bearing, basin-fill deposits as much as 3,000 feet thick. It is composed of eroded materials that vary depending on the mountains bordering the basins and the manner in which the sediments were deposited. Sediments range from the fine-grained silt and clay of lake deposits to the coarse-grained volcanic rock and limestone of alluvial fans (Figure 6-100). Freshwater saturated thickness averages about 580 feet.

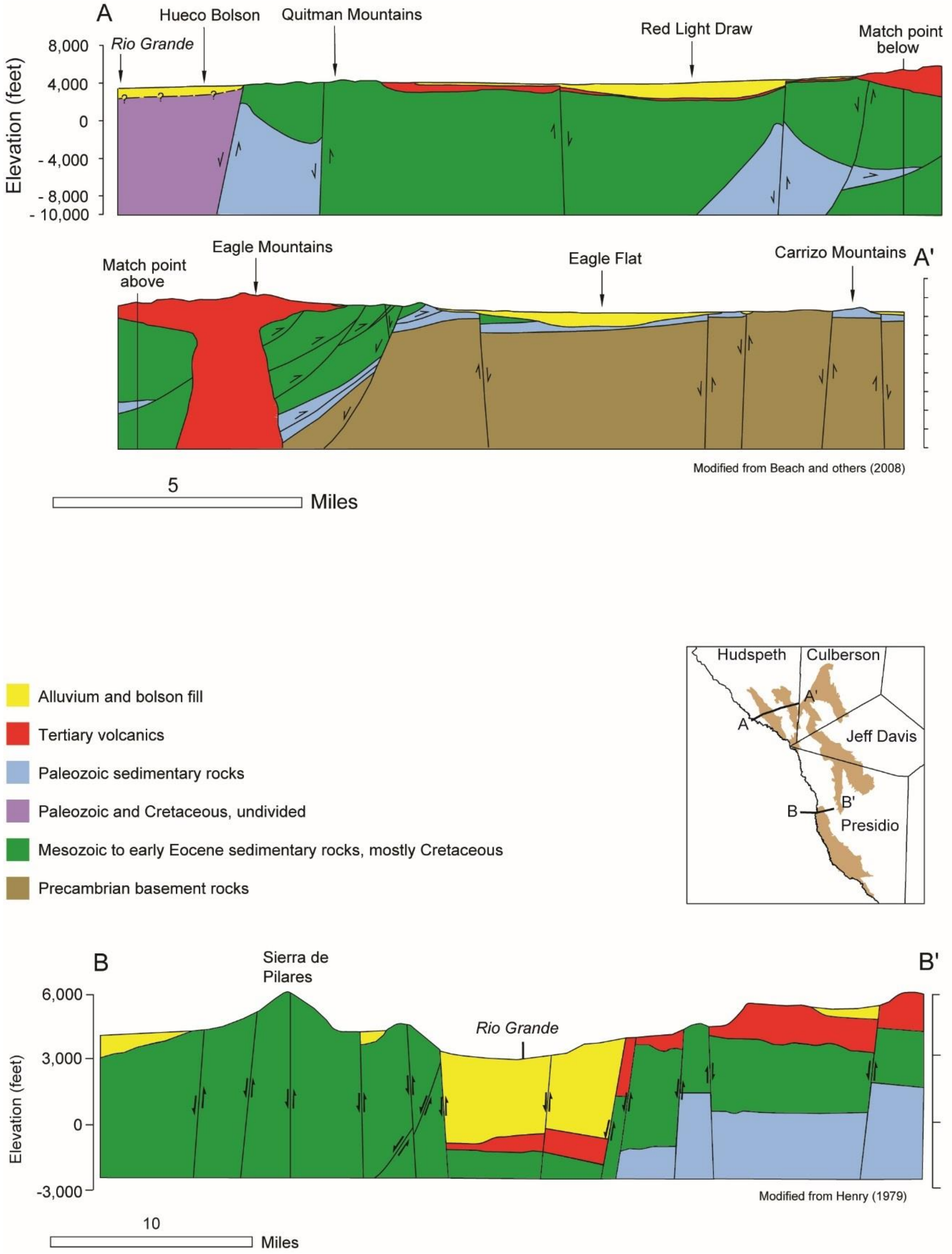


Figure 6-100. Structural cross-section across the northern West Texas Bolsons Aquifer, *above* (modified from Beach and others, 2008) and the southern Presidio Bolson, *below* (modified from Henry, 1979).

Flows to surface water and other aquifers

The Presidio and Redford bolsons discharge through springs, evapotranspiration, baseflow, and groundwater pumping. Springs include hot, thermal springs, representing deep groundwater circulation and cold springs, resulting from shallow groundwater discharge (Wade and others, 2011). Table 6-73 shows a summary of baseflow in the outcrop areas of the West Texas Bolsons Aquifer. Groundwater availability model analysis does not estimate any inter-aquifer flow between the West Texas Bolsons Aquifer and other major and minor aquifers.

Table 6-73. Summary of groundwater flow from the West Texas Bolsons Aquifer to surface water.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Culberson	450	1.8	1.7
Hudspeth	353	1	1.3
Jeff Davis	248	0.7	1
Presidio	793	2.1	3
Total	**1,844**	**6**	**7**

Water quantity

Total storage in the West Texas Bolsons Aquifer is estimated to be more than 51 million acre-feet. Recoverable storage is estimated to be between 25 and 75 percent of the total, or about 12.8 million to 38.5 million acre-feet (Table 6-74). Water levels in the West Texas Bolsons Aquifer have been declining since the 1950s, with the most significant declines occurring south of Van Horn in the Lobo Flats area and to the east in the Wild Horse Basin area.

Table 6-74. Total estimated recoverable storage in the West Texas Bolsons Aquifer, by county, in acre-feet.

County	Total storage	25 percent of storage	75 percent of storage
Culberson	5,400,000	1,350,000	4,050,000
Hudspeth	6,800,000	1,700,000	5,100,000
Jeff Davis	4,200,000	1,050,000	3,150,000
Presidio	35,000,000	8,750,000	26,250,000
Total	**51,400,000**	**12,850,000**	**38,550,000**

Water quality

Groundwater quality varies depending on the basin, ranging from freshwater, containing less than 1,000 milligrams per liter of total dissolved solids, to slightly to moderately saline water, containing between 1,000 and 4,000 milligrams per liter of total dissolved solids (Figure 6-101). Groundwater in the central and southern regions of the aquifer commonly exceeds maximum contaminant level for arsenic, fluoride, gross alpha radiation, or nitrate-N. The northern regions of the aquifer are more likely to exceed the maximum contaminant level for total dissolved solids. (Reedy and others, 2011).

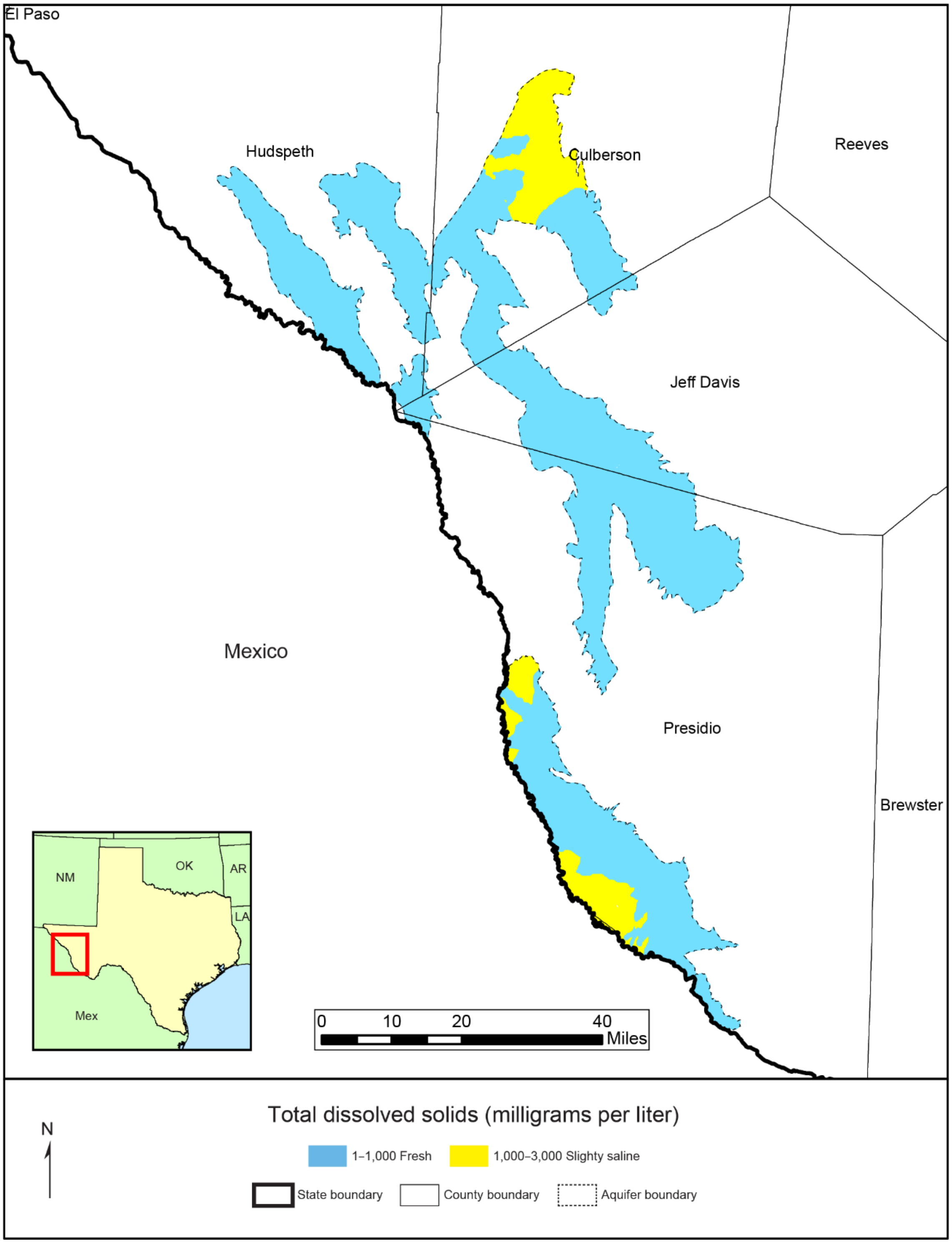


Figure 6-101. Total dissolved solids in the West Texas Bolsons Aquifer.

6.29 Woodbine Aquifer

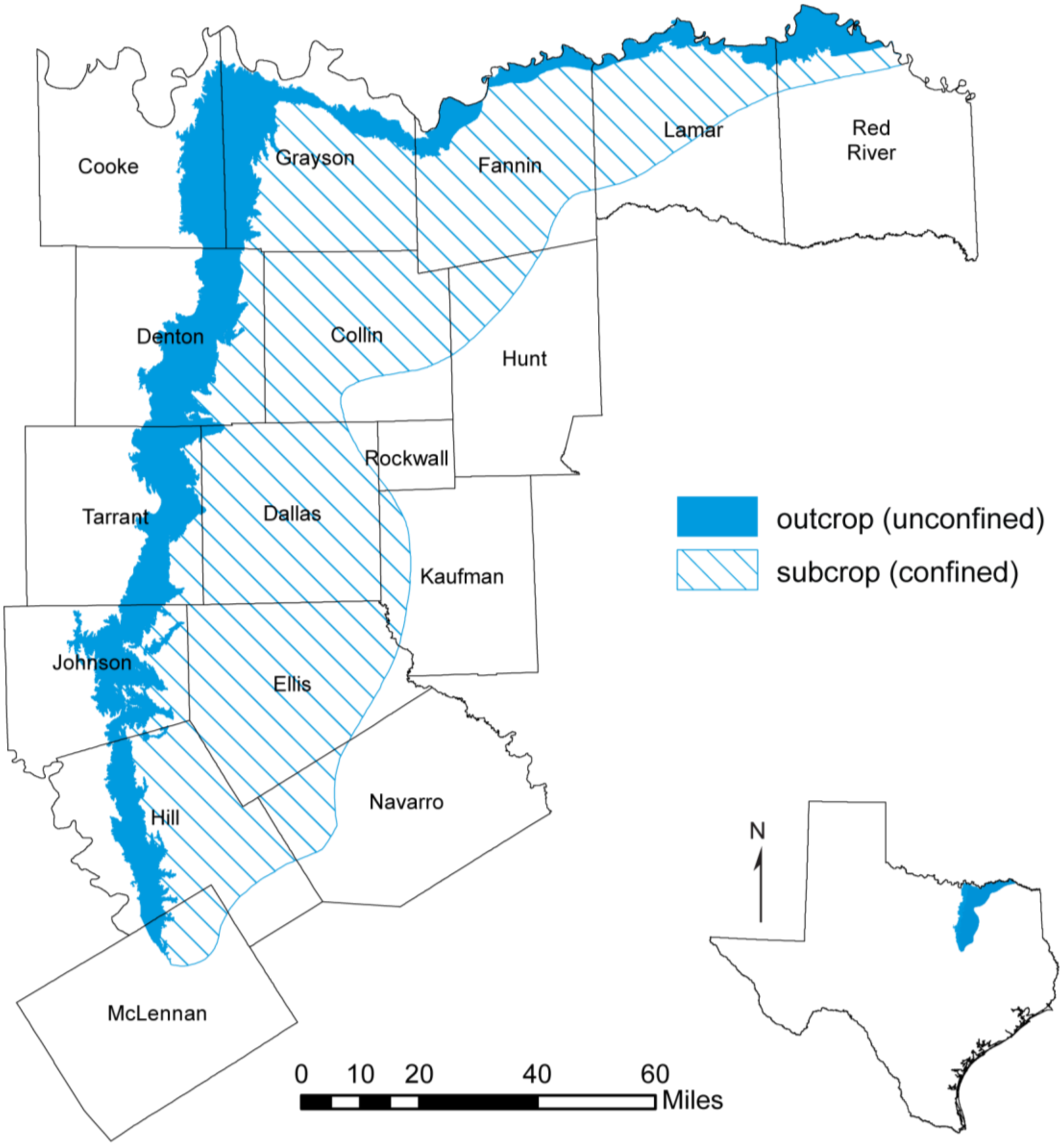


Figure 6-102. Extent of the Woodbine Aquifer.

Aquifer characteristics

- Aquifer type: confined and unconfined
- Area of outcrop: 1,561 square miles
- Area of subsurface: 5,784 square miles
- Proportion of aquifer with groundwater conservation districts: 73 percent
- Number of counties containing the aquifer: 17

Geology and hydrogeology

The Woodbine Aquifer is a minor aquifer located in northeast Texas (Figure 6-102). The aquifer overlies the Trinity Aquifer and consists of sandstone interbedded with shale and clay that form three distinct water-bearing zones (Figure 6-103). The Woodbine Aquifer reaches 600 feet in thickness in subsurface areas, and freshwater saturated thickness averages about 160 feet. Water yield varies with the depth of the aquifer. The lower zones of the aquifer typically yield the most water while the upper zone yields limited water.

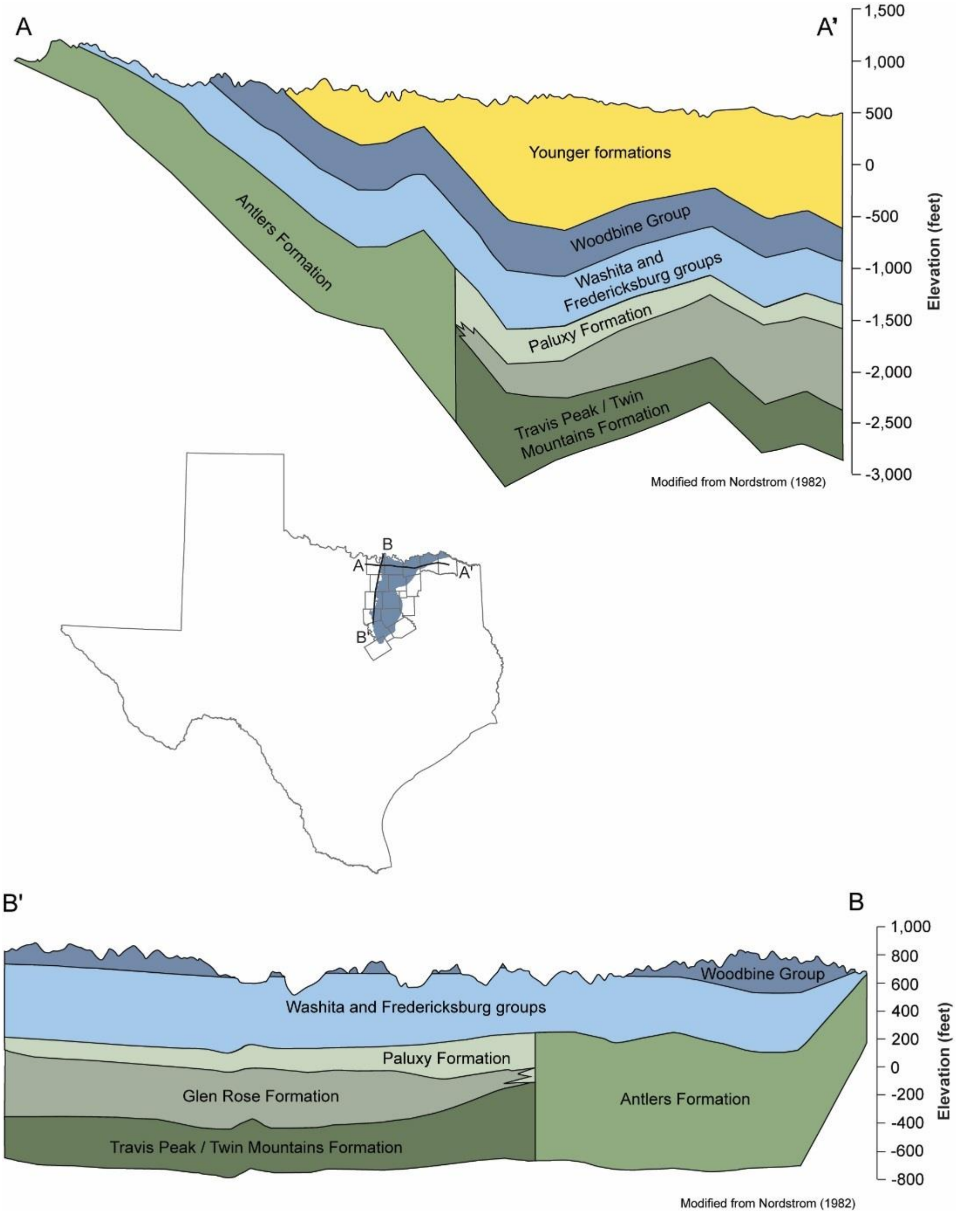


Figure 6-103. Structural cross-sections along and across Woodbine Group rocks (modified from Nordstrom, 1982).

Flows to surface water and other aquifers

Reservoirs and streams intersect the Woodbine Aquifer outcrop area. There are also springs in the area that originate in the Woodbine Aquifer (Intera, 2014). Table 6-75 summarizes baseflow in the outcrop areas of the Woodbine Aquifer. Groundwater availability model analysis does not estimate any inter-aquifer flow between the Woodbine Aquifer and other major and minor aquifers.

Table 6-75. Summary of groundwater flow from the Woodbine Aquifer to surface water, by county.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Cooke	178	10.4	1.1
Dallas	7	0.6	0.1
Denton	272	19.7	2.4
Fannin	93	9.2	2.1
Grayson	267	13.9	2
Hill	149	8.1	0.6
Johnson	191	8.5	0.6
Lamar	70	10.8	2.3
McLennan	12	0.7	0
Red River	88	9.4	0.7
Tarrant	232	10.6	1.6
Total	**1,559**	**102**	**14**

Water quantity

Total storage in the Woodbine Aquifer is estimated to be more than 227 million acre-feet. Recoverable storage is estimated to be between 25 and 75 percent of the total, or about 56.8 million to 170.5 million acre-feet (Table 6-76).

Table 6-76. Total estimated recoverable storage in the Woodbine Aquifer, by county, in acre-feet.

County	Total storage	25 percent of storage	75 percent of storage
Collin	32,000,000	8,000,000	24,000,000
Cooke	1,200,000	300,000	900,000
Dallas	30,000,000	7,500,000	22,500,000
Denton	8,900,000	2,225,000	6,675,000
Ellis	25,000,000	6,250,000	18,750,000
Fannin	39,000,000	9,750,000	29,250,000
Grayson	32,000,000	8,000,000	24,000,000
Hill	6,700,000	1,675,000	5,025,000
Hunt	8,200,000	2,050,000	6,150,000
Johnson	4,500,000	1,125,000	3,375,000
Kaufman	4,700,000	1,175,000	3,525,000
Lamar	21,000,000	5,250,000	15,750,000
McLennan	900,000	225,000	675,000
Navarro	3,400,000	850,000	2,550,000
Red River	4,500,000	1,125,000	3,375,000
Rockwall	46,000	11,500	34,500
Tarrant	5,300,000	1,325,000	3,975,000
Total	**227,346,000**	**56,836,500**	**170,509,500**

Water quality

Water quality varies with the depth of the aquifer. The upper zone tends to be very high in iron. In general, water to a depth of 1,500 feet is fresh, containing less than 1,000 milligrams per liter of total dissolved solids. Water at depths below 1,500 feet is slightly to moderately saline, containing from 1,000 to 4,000 milligrams per liter of total dissolved solids (Figure 6-104). The groundwater exceeds the maximum contaminant level for fluoride in a small percentage of wells completed in the Woodbine Aquifer (Reedy and others, 2011).

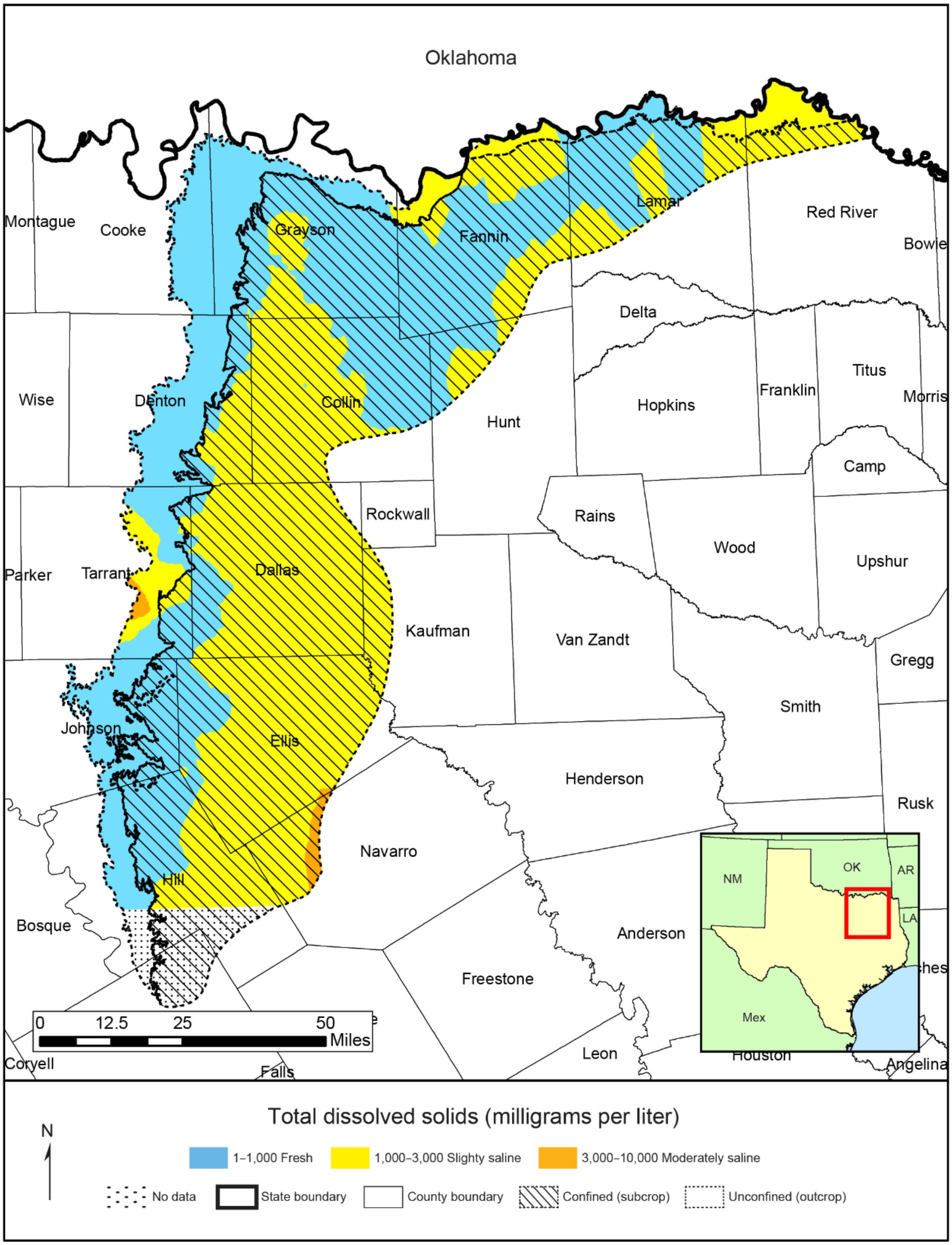


Figure 6-104. Total dissolved solids in the Woodbine Aquifer.

6.30 Yegua-Jackson Aquifer

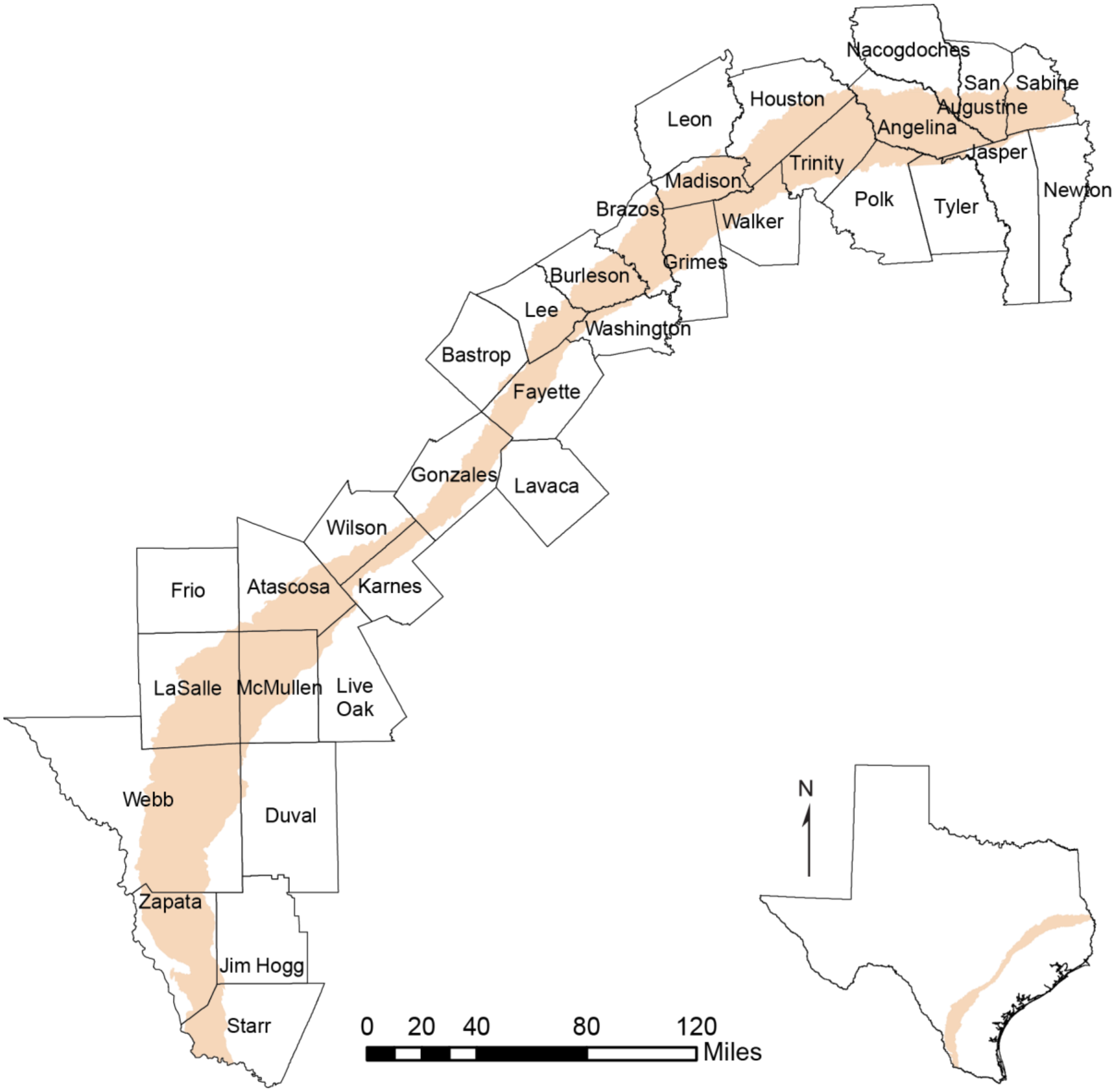


Figure 6-105. Extent of the Yegua-Jackson Aquifer.

Aquifer characteristics

- Aquifer type: unconfined
- Area of aquifer: 10,932 square miles
- Proportion of aquifer with groundwater conservation districts: 62 percent
- Number of counties containing the aquifer: 34

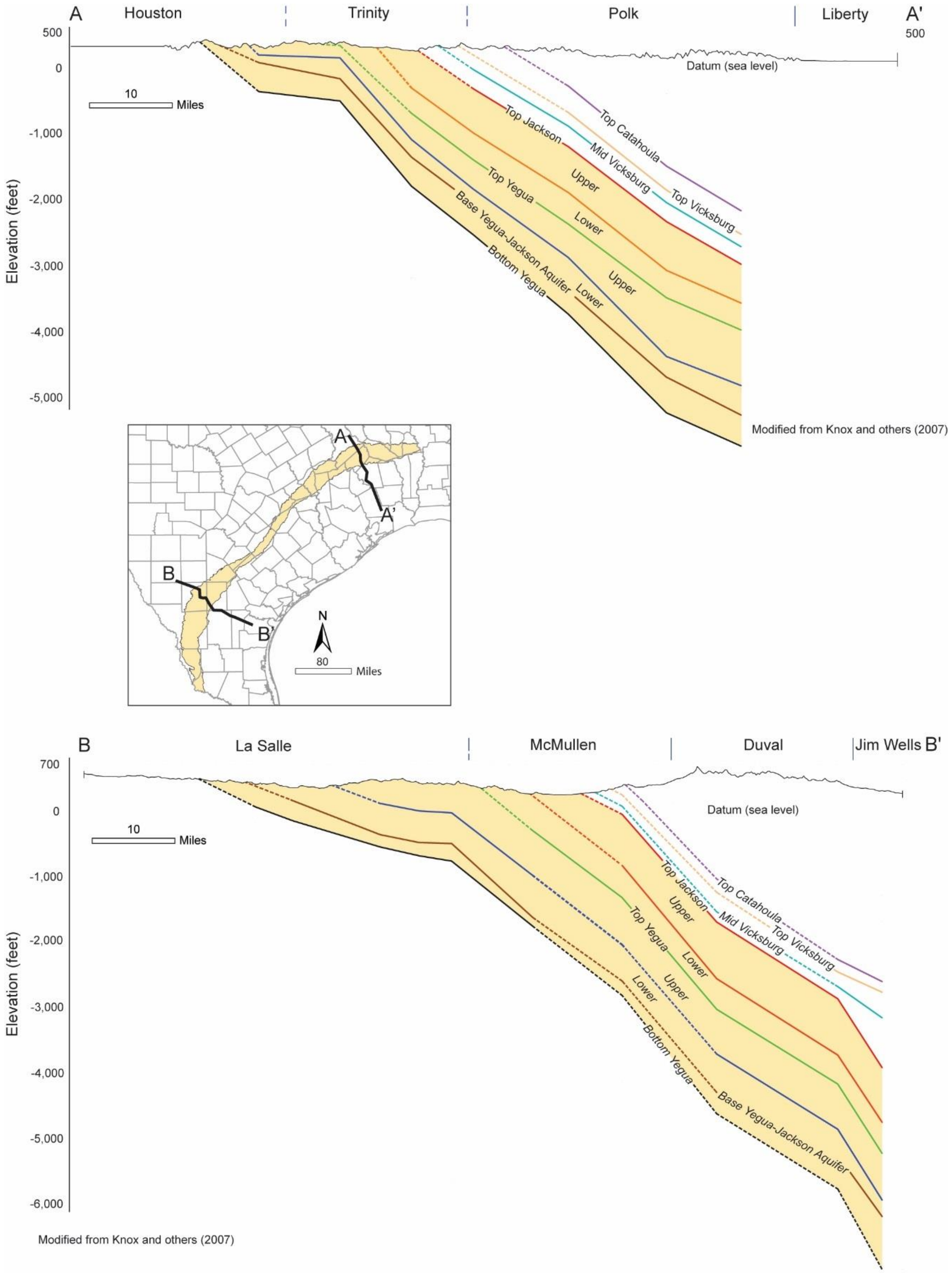
Geology and hydrogeology

The Yegua-Jackson Aquifer is a minor aquifer stretching across the southeast part of the state (Figure 6-105). It includes water-bearing parts of the Yegua Formation (part of the upper Claiborne Group) and the Jackson Group (comprising the Whitsett, Manning, Wellborn, and Caddell formations). These geologic units consist of interbedded sand, silt, and clay layers originally deposited as fluvial and deltaic sediments (Figure 6-106). Freshwater saturated thickness averages about 170 feet.

The Yegua and Jackson formations continue toward the Gulf of Mexico beyond the official boundaries of the Yegua-Jackson Aquifer, but most wells completed in the aquifer are in the outcrop area. Sand-rich intervals form the high-conductivity framework of the aquifer. Sand-rich intervals occur over most of the outcrop area of the aquifer, but down-dip there are broadly distributed areas where sand is absent, limiting groundwater productivity (Deeds and others, 2010).

Flows to surface water and other aquifers

Many rivers and streams intersect the Yegua-Jackson Aquifer outcrop. Previous studies indicate that the aquifer contributes to river and streamflow (Deeds and others, 2010). Table 6-77 shows a summary of baseflow in the outcrop areas of the Yegua-Jackson Aquifer. Groundwater availability model analysis does not estimate any inter-aquifer flow between the Yegua-Jackson Aquifer and other major and minor aquifers.



Modified from Knox and others (2007)

Modified from Knox and others (2007)

Figure 6-106. Structural cross-sections across the Yegua-Jackson Aquifer (modified from Knox and others, 2007).

Table 6-77. Summary of groundwater flow from the Yegua-Jackson Aquifer to surface water.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Angelina	739	215	68.7
Atascosa	565	29.5	10.7
Bastrop	14	0.6	0.1
Brazos	351	22.6	3.2
Burleson	258	13.9	1.5
Duval	29	0.2	0
Fayette	367	23.7	5.7
Frio	6	0.2	0.1
Gonzales	437	38	9.8
Grimes	352	29.7	2.9
Houston	515	102.7	30.1
Jasper	36	11.8	4.2
Jim Hogg	10	0.1	0
Karnes	188	14.3	5.1
La Salle	905	10.4	2.5
Lavaca	1	0.1	0
Lee	227	20.8	3.1
Leon	6	0.6	0.1
Live Oak	56	1.5	0.5
Madison	391	30.4	3.4
McMullen	747	10.4	2.5
Nacogdoches	55	16.8	5
Newton	4	1.2	0.3
Polk	136	38.3	10.3
Sabine	309	85.6	23.9
San Augustine	262	77.5	22.2
Starr	252	7.6	1.2
Trinity	622	103.3	28.4
Tyler	47	14.8	4.9
Walker	249	26.4	3.7
Washington	80	5.6	0.6
Webb	1549	10.5	1.8
Wilson	193	16.5	6.4

Table 6-77 (continued). Summary of groundwater flow from the Yegua-Jackson Aquifer to surface water.

County	Area of aquifer outcrop in county (square miles)	Sum of average annual baseflow (cubic feet per second)	Sum of median annual baseflow (cubic feet per second)
Zapata	757	5.8	1.5
Total	**10,715**	**986**	**264**

Water quantity

Total storage in the Yegua-Jackson Aquifer is estimated to be more than 1 billion acre-feet. Recoverable storage is estimated to be between 25 and 75 percent of the total, or about 300.6 million to 901.8 million acre-feet (Table 6-79).

Table 6-78. Total estimated recoverable storage in the Yegua-Jackson Aquifer by county, in acre-feet.

County	Total storage	25 percent of storage	75 percent of storage
Angelina	72,000,000	18,000,000	54,000,000
Atascosa	40,000,000	10,000,000	30,000,000
Bastrop	290,000	72,500	217,500
Brazos	30,000,000	7,500,000	22,500,000
Burleson	27,000,000	6,750,000	20,250,000
Duval	7,200,000	1,800,000	5,400,000
Fayette	27,000,000	6,750,000	20,250,000
Frio	75,000	18,750	56,250
Gonzales	32,000,000	8,000,000	24,000,000
Grimes	94,900,000	23,725,000	71,175,000
Houston	21,000,000	5,250,000	15,750,000
Jasper	6,930,000	1,732,500	5,197,500
Jim Hogg	3,000,000	750,000	2,250,000
Karnes	19,190,000	4,797,500	14,392,500
La Salle	56,000,000	14,000,000	42,000,000
Lavaca	620,000	155,000	465,000
Lee	10,000,000	2,500,000	7,500,000
Leon	76,000	19,000	57,000
Live Oak	11,000,000	2,750,000	8,250,000
Madison	15,000,000	3,750,000	11,250,000

Table 6-78 (continued). Total estimated recoverable storage in the Yegua-Jackson Aquifer by county, in acre-feet.

County	Total storage	25 percent of storage	75 percent of storage
McMullen	96,000,000	24,000,000	72,000,000
Nacogdoches	1,400,000	350,000	1,050,000
Newton	1,270,000	317,500	952,500
Polk	27,900,000	6,975,000	20,925,000
Sabine	30,000,000	7,500,000	22,500,000
San Augustine	19,000,000	4,750,000	14,250,000
Starr	46,000,000	11,500,000	34,500,000
Trinity	83,000,000	20,750,000	62,250,000
Tyler	8,650,000	2,162,500	6,487,500
Walker	103,000,000	25,750,000	77,250,000
Washington	12,400,000	3,100,000	9,300,000
Webb	210,820,000	52,705,000	158,115,000
Wilson	6,800,000	1,700,000	5,100,000
Zapata	83,000,000	20,750,000	62,250,000
Total	**1,202,521,000**	**300,630,250**	**901,890,750**

Water quality

Water quality varies greatly due to sediment composition in the aquifer formations, and in all areas the aquifer becomes highly mineralized with depth. Most groundwater is produced from the sand units of the aquifer, where the water is fresh and ranges from less than 50 to 1,000 milligrams per liter of total dissolved solids. Some slightly to moderately saline water, with concentrations of total dissolved solids ranging from 1,000 to 10,000 milligrams per liter, also occurs in the aquifer (Figure 6-107). There is low probability for maximum contaminant level exceedances in the aquifer. However, the southern part of the aquifer tends to have moderate levels of total dissolved solids, iron, and manganese exceedances (Reedy and others, 2011).

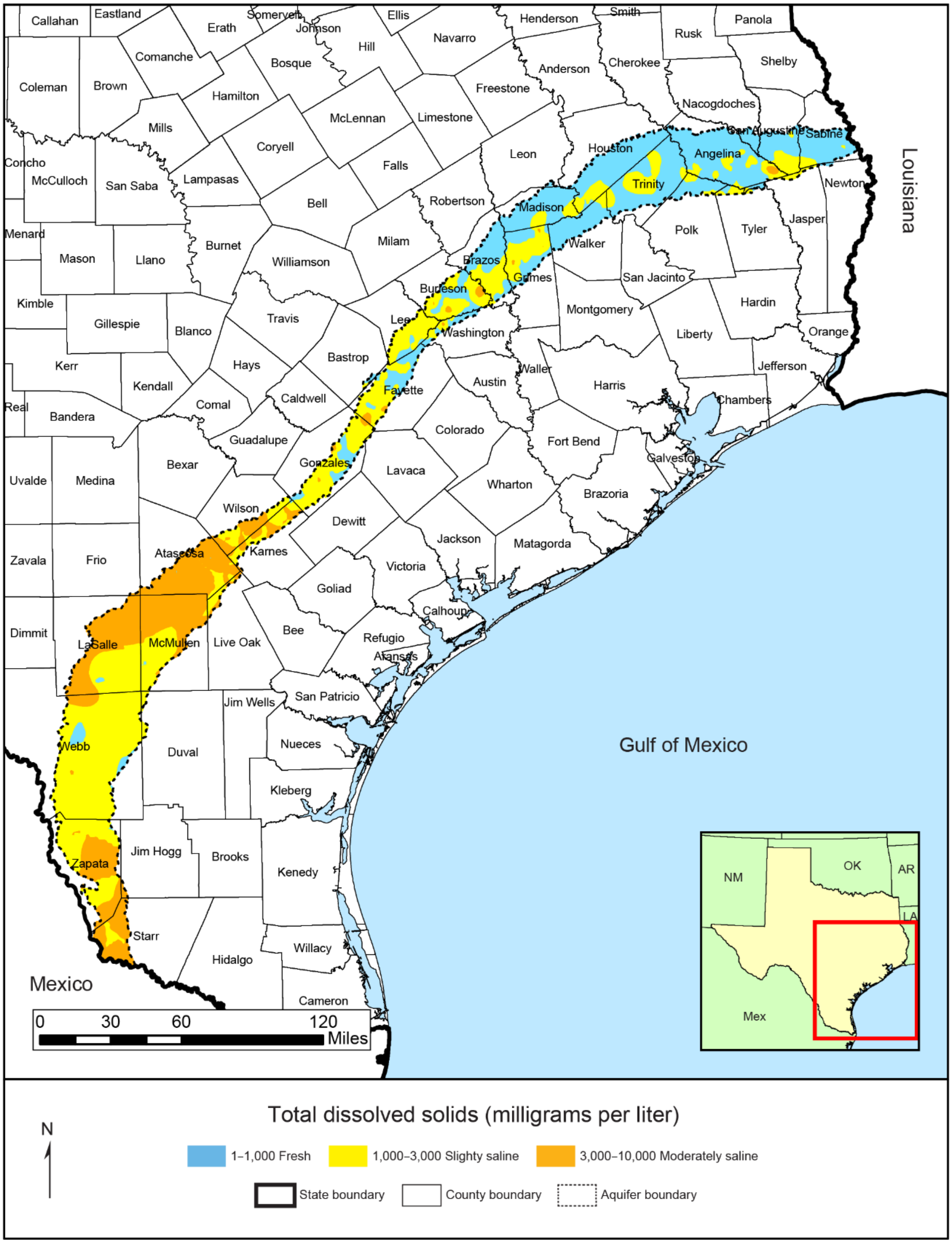


Figure 6-107. Total dissolved solids in the Yegua-Jackson Aquifer.

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